1ST PATENT of Level 1 printed in FULL format.

6,388,815

<=2> GET 1st DRAWING SHEET OF 18

May 14, 2002

Device and method for producing optically-controlled incremental time delays

INVENTOR: Collins, Jr., Stuart, Worthington, Ohio
Anderson, Betty Lise, Gahanna, Ohio

ASSIGNEE-AT-ISSUE: The Ohio State University, Columbus, Ohio [02] United States Company or Corporation

APPL-NO: 645,136 (Series 9)

FILED: August 24, 2000

INT-CL: [7] G02B 27#14; G02F 1#00

US-CL: 359#633; 359#631; 359#237; 359#291; 359#290

CL: 359

SEARCH-FLD: 359#290, 291, 245, 237, 871, 629, 631, 633; 385#140; 310#306, 307

REF-CITED:

U.S. PATENT DOCUMENTS

4,225,938	9/1980	*	Turpin	708#816
4,474,434	10/1984	*	Carlsen et al.	359#320
4,474,435	10/1984	*	Carlsen et al.	359#320
5,117,239	5/1992	*	Riza	342#375
5,319,477	6/1994	*	DeJule	359#42
5,463,497	10/1995	*	Muraki et al.	359#619
5,465,175	11/1995	*	Woodgate et al.	359#619
5,512,907	4/1996	*	Riza	342#375
5,936,759	8/1999	*	Buttner	359#291
6,064,506	5/2000	*	Koops	359#237
6,266,176	7/2001	*	Anderson	359#245

OTHER PUBLICATIONS

Collins, Jr et al., Optical True Time Delay for Phased Array Antennas Based on the White Cell, GOMA, Monterey, California, 4 pp. (Mar., 1999).
Anderson et al., Design Advances in Free-Space Optical True-Time Delay Device, PSAA-8, Monterey, California, 4 pp. (Jan., 1998).
Anderson et al., Binary-Counting True Time Delay Generator Using a White Cell Design and Deformable Mirror Devices, LEOS, Orlando, Florida, 2 pp. (Dec., 1998).
Anderson et al., Highly Parallel Optical Device to Produce True Time Delays for Phased Array Antennas, Allerton, 14 pp. (Sep., 1998).
Anderson et al., Optically Produced True-Time Delays for Phased Antenna Arrays, Applied Optics, vol. 36, No. 32, pp. 8493-8503 (Nov. 1997).
Collins et al., Optics for Numerical Calculation, Proceedings of ICO-11

Conference, Madrid, Spain (1978).
Collins, Numerical Optical Data Processor, SPIE vol. 128, Effective Utilization of Optics in Radar Systems, pp. 313-319 (1977).
Collins et al., Numerical Optical Data Processing, Proceedings of the 1978 International Optical Computing Conference, London, England, pp. 194-197 (Sep., 1978).
Yen et al., Operation of a Numerical Optical Data Processor, International Optical Computing Conference, SPIE Proceedings, vol. 232, 8 pp. (1980).

PRIM-EXMR: Epps, Georgia

ASST-EXMR: O'Neill, Gary

LEGAL-REP: Standley & Gilcrest LLP

CORE TERMS: lens, mirror, beam, optical, cell, delta, plane, spot, input, auxiliary, curvature, modulator, spatial, path, ray, theta, equation, bounce, prism, turning, alpha, glass, conjugate, matrix, imaged, pixel, imaging, polarization, min, time delay

ABST:
The present invention includes time delay devices and time delay systems. The invention also includes machines and instruments using those aspects of the invention. The invention may also be used to upgrade, repair, or retrofit existing machines or instruments, using methods and components known in the art. The present invention comprises a true time device that falls into the free-space category but uses a multiple-pass optical cell with refocusing mirrors that has the advantage of avoiding beam-spreading problems. This approach differs from previous free-space approaches in that it uses only one optical switch or spatial light modulator instead of one or more switches for each bit. In one approach, a microwave signal for each antenna element may be modulated onto an optical beam. After the individual optical beams are delayed by the desired amount of time through the system, the signals may then be down-converted to microwave signals for further processing. This process may be used in either the transmit or the receive mode of a phased array radar.

NO-OF-CLAIMS: 27

EXMPL-CLAIM: <=14> 1

NO-OF-FIGURES: 26

NO-DRWNG-PP: 17

SUM:

TECHNICAL FIELD OF THE INVENTION

The present invention is in the field of time delay devices, such as those that may be used for the control of phased-array radars, communication systems, or correlators.

BACKGROUND OF THE INVENTION

This invention relates to apparatus for producing true-time delay devices, such as those useful in the control of phased array radars. It is desirable to use a system that produces signals to control the timing of the emission of each of a plurality of electromagnetic radiation beams, delaying each of them in time by some time increment. The delay in each signal should be capable of being controlled independently of the other signals.

Phased array radars have the advantage that the radar beams can be steered electronically by changing the phase or timing of the signal radiated by the individual elements of the array. Often, this is accomplished by controlling the phase of the signals applied to the array elements. This procedure introduces undesirable squint if very short pulses or broad bandwidths are required. True time delay offers a scheme for controlling the elements without squint even with broadband signals.

Electronically implementing the true time delays is generally impractical because of the need for many long lengths of strip line, waveguides, or coaxial cable, which are expensive, bulky, and temperature sensitive. Because long paths are comparatively easy to obtain optically, photonic systems present a means of obtaining the beam agility of array systems combined with wide bandwidth. Approaches to true time delay tend to fall into two categories: those using fibers and those using long free-space paths. Some fiber approaches use multiple optical switches or broadcast the light over all possible paths at once. Wavelength-division-multiplexing schemes have recently been developed by use of fiber Bragg gratings. Free-space systems have also used multiple optical switches for switching the beams between sequential optical paths. These optical switches are usually liquid-crystal based.

It is therefore an object of the current invention to create a device for optically generating true time delays that is inexpensive, is compact in design, and is sufficiently temperature insensitive.

Although described with respect to the field of phased-array radars, it will be appreciated that similar advantages of optically producing true-time delays, as well as other advantages, may obtain in other applications of the present invention. Such advantages may become apparent to one of ordinary skill in the art in light of the present disclosure or through practice of the invention.

SUMMARY OF THE INVENTION

The present invention includes time delay devices and time delay systems. The invention also includes machines and instruments using those aspects of the invention. The invention may also be used to upgrade, repair, or retrofit existing machines or instruments, using methods and components known in the art.

The present invention comprises a true time device that falls into the free-space category but uses a multiple-pass optical cell with refocusing mirrors that has the advantage of avoiding beam-spreading problems. This approach differs from previous free-space approaches in that it uses only one optical switch or spatial light modulator instead of one or more switches for each bit. In this approach the microwave signal for each antenna element may be modulated onto an optical beam. After the individual optical beams are delayed by the desired amount of time, the signals may then be down-converted to microwave signals for further processing. This process may be used in either the transmit or the. receive mode of the phased array radar.

In broadest terms, the device for producing optically-controlled incremental time delays of the present invention comprises: (1) an input device selected from the group comprising light sources adapted to generate individual light beams or arrays of light beams from one or several directions, (2) an adjustable input mirror capable of reflecting light from the input device in different directions, (3) a set of optical elements selected from the group consisting of mirrors, lenses, filters and prisms placed in a configuration so as to define a multitude of light paths for each light beam from the input device reflected by the adjustable input mirror, (4) at least one refocusing element to restrict the divergence of a light beam directed through at least one of the light paths, (5) a spatial light modulator adapted to select a path from among the light paths for each pass through the set of optical elements of an individual light beam from the input device, (6) an output mirror adapted to reflect the light beams emerging from the set of optical elements, and (7) a receiving device capable of responding to the delays in the light beams reflected by the output mirror.

The device for producing optically-controlled incremental time delays of the present invention may also include at least one system of optical transmission lines or waveguides wherein the lengths of the light paths may be varied in a confined space consisting of a subset of the optical elements. The spatial light modulator may consist of a polarizing spatial light modulator which changes the polarization of individual light beams directed to the spatial light modulator. The use of a polarizing spatial light modulator then may require the addition of a beam-splitting device that can direct light beams through the system of optical elements in multiple directions depending on the polarization of the light beams after passing through the polarizing spatial light modulator. The device may alternatively include a micromechanical or deformable mirror device spatial light modulator capable of reflecting the individual light beams in multiple directions, thereby determining the optical path.

The light sources adapted to generate individual light beams or arrays of light beams from one or several directions may include such devices as lasers, arc lamps, and light emitting diodes. The receiving devices capable of responding to the delays may include devices such as photodetectors, pin diodes, photodiodes, and interferometers.

DRWDESC:

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a top view of a standard White cell on which the present invention is based.

FIG. 2 is a front elevational view of the spatial light modulator, along with one embodiment of the input and output mirrors in accordance with the present invention.

FIG. 3 is a top view of the dual-arm cell with a beam splitter in accordance with one embodiment of the present invention.

FIG. 4 is a top view of a quadratic cell, where the distances from the spatial light modulator to the White cell mirrors vary, in accordance with one embodiment of the present invention.

FIG. 5 is a perspective view of the dual arm cell with a set of glass blocks and auxiliary mirror in accordance with one embodiment of the present

invention.

FIG. 5a is another perspective view of the dual arm cell in accordance with one embodiment of the present invention.

FIG. 6 is a diagram of a White cell using a deformable mirror device spatial light modulator and an appropriate prism in accordance with one embodiment of the present invention.

FIG. 7 is a diagram of a multiple arm version of the deformable mirror device configuration in accordance with one embodiment of the present invention.

FIG. 8 is a perspective view of an alternative cell configuration in accordance with one embodiment of the present invention.

FIG. 9 is a side elevational view of a system of lens groups in accordance with one embodiment of the present invention.

FIG. 10 is another side elevational view of the image planes in the optical transmission line in accordance with one embodiment of the present invention.

FIG. 11 is a ray diagram for a spherical mirror in accordance with one embodiment of the present invention.

FIG. 12 is another ray diagram of a spherical mirror/lens system in accordance with one embodiment of the present invention.

FIG. 13 is a plot of path distances in accordance with one embodiment of the present invention.

FIG. 14a is a ray diagram of a deformable mirror device in accordance with one embodiment of the present invention.

FIG. 14b is another ray diagram in accordance with one embodiment of the present invention.

FIG. 15 is a ray diagram for a small angle prism in accordance with one embodiment of the present invention.

FIG. 16a is a diagram showing spot location on a deformable mirror device in accordance with one embodiment of the present invention.

FIG. 16b is another diagram showing spot location on a deformable mirror device in accordance with one embodiment of the present invention.

FIG. 16c is another diagram showing spot location on a deformable mirror device in accordance with one embodiment of the present invention.

FIG. 17 is another diagram showing spot location on a deformable mirror device in accordance with one embodiment of the present invention.

FIG. 18 is another diagram showing spot location on a deformable mirror device in accordance with one embodiment of the present invention.

FIG. 19a is a diagram of reflected planes in accordance with one embodiment of the present invention.

FIG. 19b is another diagram of reflected planes in accordance with one embodiment of the present invention.

FIG. 20a is a diagram of a light beam incident on a DMD in accordance with one embodiment of the present invention.

FIG. 20b is another diagram of a light beam incident on a DMD in accordance with one embodiment of the present invention.

DETDESC:

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT(S)

In accordance with the foregoing summary, the following presents a detailed description of the preferred embodiment of the invention that is currently considered to be the best mode.

The present invention is based on the traditional White cell. FIG. 1 is a diagram of the path of a light beam passing through a White cell. The cell comprises three identical spherical mirrors, all of the same radius of curvature. The first mirror 12 is separated from the second 13 and third 14 mirrors by a distance equal to their radii of curvature. The center of curvature 15 of the first mirror lies on the centerline or optical axis 16 and falls between the second and third mirrors. The second and third mirrors are aligned so that the center of curvature 20 of the second mirror 13 and the center of curvature 19 of the third mirror 14 land on the first mirror, for example an equal distance from the optical axis. Light from the second mirror is imaged onto the third mirror, and vice versa. Light is input onto a spot 18 in the plane of but off the edge of the first mirror; the light beam is prepared so that it expands as it goes to the third mirror. The third mirror refocuses the beam to a point on the first mirror. The beam is then reflected to and expanded at the second mirror. The second mirror refocuses the light beam to a new spot 17 on the first mirror. At this point, the light may either exit the cell if the spot is off the edge of the first mirror, or continue to traverse the cell. The beam may traverse the cell a predetermined number of times, depending on the locations of the centers of curvature of the second and third mirrors.

The angle of the input beam may be controlled by an input turning mirror 21, as shown in FIG. 2. The angle of the output beam may similarly be controlled by an output turning mirror 22. Each bounce of a light beam is shown by a spot 23 on the turning mirrors or the first mirror 12. There are multiple light beams shown. A spatial light modulator or other appropriate device may alternatively replace the first mirror. A beam of light may be reflected off the input turning mirror into the White cell, and may traverse the cell until the beam is directed to the output turning mirror, at which point it may exit the cell.

FIG. 3 shows a first modification to the White cell to adapt it to variable time delay applications. A first modification is to change. the first mirror 12 from a curved mirror to a flat one and to add a lens 27 of focal length such that the lens-mirror. combination is optically equivalent to the mirror it replaces. Next, the flat mirror may be replaced with a spatial light

modulator. This particular spatial light modulator may be configured to rotate the direction of polarization of the reflected beam by ninety degrees at. any particular pixel that is activated. Then, a polarizing beam splitter 28 may be added, and the distances to the second 13 and third 14 mirrors may be adjusted to maintain imaging. The input light may be polarized in the plane of the paper. The beam splitter may reflect. light polarized in the plane perpendicular to the paper but transmit light polarized parallel to the plane of the paper.

A better photonic device may be implemented by next adding a fourth 24 and fifth 25 mirror, where these mirrors are identical but have a focal length different than that of the second and third mirrors. There now exist dual cells joined at the beam splitter. Since the single lens 27 can no longer satisfy the focusing conditions for both cells, a lens 26 of different focal length may be added to the other output side of the beam splitter. The focal lengths of the lenses are chosen to compensate for the new mirror locations.

Yet a better photonic device may be obtained if the distances to the fourth and fifth mirrors from the beam splitter are different, as shown in FIG. 4. In this case the radii of curvature of the fourth and fifth mirrors will be different. An additional lens or lenses may be added between lens 26 and mirror 25a to maintain imaging.

To improve the number of potential time delays, the design of the dual-armed unit of FIG. 3 may be further modified. This configuration is shown in FIG. 5. First, auxiliary mirror 29 may be added in the plane of the spatial light modulator 12. A second auxiliary mirror may be placed in the image plane of the spatial light modulator. Then, a time delay mechanism such as a set of glass blocks 30 may be substituted for this second auxiliary mirror, as shown in FIG. 5a. The blocks are reflective on the sides furthest from the lens 41. Alternatively, the glass blocks could be replaced by optical fibers or an array of fibers. The optical axis is between the spatial light modulator and the auxiliary mirror. The first lens 27 has been made larger to cover them. The thicknesses of the glass blocks may be chosen so that the additional time required for the beams to go through successive blocks increases as powers of two times the initial thickness. The operation is comparable to that of the dual cell with the plane of the spatial light modulator enlarged and additional time delays due to the addition of the glass blocks or equivalent transparent materials.

If a deformable mirror device spatial light modulator 31 is used, a simple White cell can be constructed as shown in FIG. 6. A prism 32 may be used to direct the light beam through a focusing lens 33 onto the appropriate mirror 34 off the optical axis. FIG. 7 also shows that another prism 37 may be introduced to direct light from the deformable mirror device spatial light modulator 31 through a refocusing lens 38 onto the other off-axis mirror 39 in the dual-arm configuration.

Another possible configuration of the dual arm cell is shown in FIG. 8. Here, the second and third mirrors of the first arm of the original device are replaced by the second 35 and third 39 mirrors of the new configuration. The fourth and fifth mirrors that comprised the second arm of the original device are then replaced by the second mirror 35 again, along with the first mirror 34 of the new configuration. Then, light beams may bounce from the second or third mirrors to the first or second mirrors, then back to the second or third mirrors, mimicking the operation of the original dual-arm cell. An additional

lens 40 may be used to image the spatial light modulator onto an auxiliary mirror 29, and a lens 41 may be used to image the spatial light modulator onto a delay mechanism such as glass blocks 30.

A prism such as 32 and its adjacent lens such as 33 may be replaced with a single lens that is appropriately tilted or decentered or both.

In order to obtain longer time delays, it is possible to introduce a lens waveguide in place of the glass blocks. FIG. 9 shows such a lens waveguide. Three lenses 42 form a lens group 43. The lens groups may then be placed along a common optical axis to form an optical transmission line or lens waveguide. The light comes into the optical transmission line from the right. The input plane 44 is coincident with an auxiliary mirror plane. At the left of each lens group is an additional plane conjugate to the auxiliary mirror plane. A transparent material may be placed at these conjugate planes, as shown in FIG. 10. Each sheet of transparent material 45 may have a reflective strip 46 on a portion of its surface. This permits light beams incident on different areas of the waveguide to propagate through different lengths of the optical transmission line.

Materials and Methods

Imaging Conditions. An analytical description of one arm of the White cell is presented. The configuration to be described is shown in FIG. 3. At the right of the figure, a White cell spherical mirror B 14 is shown below the axis and a White cell mirror C 13 above the axis. The center of curvature of White cell mirror B is a distance [delta] [1]above the optical axis. The center of curvature of Mirror C is a distance [delta] [2]below the optical axis. To the left of the White cell mirrors is lens f127 with focal length f[1]. Adjacent to it is the polarizing prism 28 represented by a cube of glass of side d, and next to that is a flat mirror perpendicular to the optical axis representing the SLM. To present the analytical description of the imaging requirements, optical ray matrices are used. These matrices operate on a column vector <=15> Get Mathematical Equation

where y, n, and p[y]refer to the projection of a ray on the y-z plane. The vector element y represents the displacement of the ray from the optical (z) axis at some value of z. The element p[y]represents the slope of the ray at that point and n is the refractive index in the region. The third matrix element "1" is used in representing a tilted spherical mirror as will be shown later. A similar analysis could be used with y replaced by x and p[y]replaced by p[x]for the projection of the ray on the x-z plane. 3 x 3 ray matrices are used because they will be useful in representing the tilted spherical mirrors. Three ray matrices are used. The first is the matrix T(d, n), representing a translation through a material of refractive index n by a distance d in the axial direction. <=16> Get Mathematical Equation

The second is the matrix L(f) representing a thin lens of focal length <=17> Get Mathematical Equation

The thin lens matrix is identical with that of a spherical mirror of focal length f with its center of curvature on the axis.

A last matrix represents a spherical mirror tilted so that a line from the intersection of the mirror and the optical axis to the center of curvature,

point CC, makes an angle [theta] with the optical axis. A ray comes from the lower left with slope p[yl]reflecting off the mirror at point P and leaving with slope P[y2]. Line CCP is drawn from point P through the center of curvature. There are two lines parallel to the axis, one through the center of curvature and one through point P. Line CCP makes angle [alpha] [1]with the incoming ray and angle [alpha] [2]with the reflected ray, as shown in FIG. 11. The center of curvature is a distance [delta] above the optical axis, and point P is a distance y above the optical axis and a distance y' above point CC.

Then there are five equations. Since the angle of incidence equals the angle reflection, [alpha] [1] = [alpha] [2]. For small angles [alpha] [1] = p[yl] - (y'/R) and [alpha] [2] = P[y2] + (y'/R). Also, y = y' + [delta] and [delta] = [theta] R = 2 [theta] f, where f is the focal length of the mirror. Combining these equations to eliminate [alpha] [1], [alpha] [2], y', and R, gives p[y2] - [theta] = p[yl] + [theta] - y/f, the equation relating p[yl], the ray slope before reflection off the spherical mirror with p[y2], the ray slope after reflection. This leads to the ray matrix M(f [theta]): [theta] [theta] <=18> Get Mathematical Equation

To use these matrices in practice, one identifies the translations and thin lenses and mirrors encountered as a ray traverses an optical system and multiplies the associated matrices together to represent the effect of the optical system on the ray. Call the product matrix S. Then there results a matrix equation representing the ray slope-index products at the input and output n[1]p[yl]and n[2]p[y2]and the displacements of the ray from the axis at the input and output, y[1]and y[2]. <=19> Get Mathematical Equation

This represents three simultaneous equations. For example, the first such equation is y[2] = Ay[1] + B n[1]p[yl] + G. This equation nicely relates the input and output ray positions. The requirement that there be imaging between the input and output planes is that matrix element B = 0. That requirement allows solving for the desired distances or focal lengths.

To return to the optical system, there are four requirements for proper operation. The first requirement is that Mirror B be imaged onto Mirror C so that no light will be lost by rays starting from Mirror B and missing Mirror C. To establish this requirement the system matrix S(B, C) is calculated for rays traversing from Mirror B to Mirror C. It is S[(B,C)] = T(d, 1)L(f[1])T(2d[1], n[1])L(f[1])T(d, 1). Inserting d, d[1]and f[1]in the appropriate matrices and multiplying the matrices together yields [][] [[][]] [[]][] <=20> Get Mathematical Equation

The requirement that Mirrors B and C be conjugates then is that matrix element B be zero: 2[(1 - [d/f[1]])(d + (d[1]/n[1])(1 - [d/f[1]]))] = 0. This is used to give the desired focal length for lens f[1]. There are two solutions: f[1] = d and f[1] = d/(1 + [n[1]d/d[1]]). These solutions represent symmetric and anti-symmetric ray patterns about the SLM. In the first solution a point on Mirror B has an image at infinity which gives an image on Mirror C with a magnification of - 1. In the second solution a point on Mirror B has an image on the SLM. This also gives an image on Mirror C with a magnification of + 1. The first solution works very nicely for this situation. This puts Mirrors B and C in the focal plane of lens f1. The same analysis applies to Mirrors E 25 and F 24 and lens f226. Mirrors E and F are in the focal plane of lens f2.

The second requirement is that Mirrors E and F be images of each other.

Considering requirements three and four that a point on the SLM be imaged back onto itself through each cell, take f to be the focal length of mirror B. The system matrix for that case is given by S = T(d[1],n[1])L(f[1])T(d,1)L(f [theta])T(d,1)L(f[1])T(d[1],n[1]). Multiplying the appropriate matrices together and putting f[1] = d as required by the first imaging condition results in [] <=21> Get Mathematical Equation

The imaging condition is then B = 0 = 2(d - [d[1]/n[1]]) - (d<2>/f), or f = d/[2(1 - [d[1]/n[1]d])]. This equation allows predicting the required focal length for the spherical mirrors.

The equation also has some interesting implications leading to physical meaning, as explained by FIG. 12. For the first one, consider the image of the center of curvature of Mirror B through lens f1. The radius of curvature of Mirror B is 2f and the distance of its center of curvature from lens f1 is d - 2f. Then the distance of the image from the center of curvature, call it d[cc], is given by 1/d[cc] + 1/(d - 2f) = 1/f[1]. Eliminating f in these equations and simplifying results in d[cc] = d[1]/n[1]. That is, the image of the center of curvature of Mirror B lies on the SLM surface. The image of the center of curvature of mirror B on the SLM can be called the center of curvature point.

To find out where on the SLM surface the center of curvature point is located, look to the magnification. The y value of the image of the center of curvature point, call it y[cci]is given by the y value of the center of curvature itself, Y[cco], times the magnification, or y[cc] = y[cco] x magnification = 2f [theta] x (- image distance/n[1])/(object distance) = 2f [theta] x [- d[1]/(n[1][d - 2f])]. Using a previous equation for 2f and simplifying gives y[cc] = [theta] d, which has a very nice interpretation. If a line is drawn from the intersection of the optical axis with Mirror B through the center of curvature of Mirror B, then the intersection of that line, extended if necessary, with lens f1 is a distance [theta] d from the axis. The projection of that intersection onto the SLM gives the center of curvature point.

There is a further interpretation in terms of point sources on the SLM that are imaged back onto the SLM. Writing the first linear equation for the system matrix gives y[2] = - y[1] + 2 [theta] d. Here, y[1]is the location of a point source on the SLM and y[2]is the location of its image after the light from the source has passed through lens f1, been reflected off Mirror B and passed back through lens f1. Defining [delta] = [theta] d and rewriting this equation gives (y[2] - [delta]) = - (y[1] - [delta]). This is interpreted in terms of a distance [delta] . The interpretation is that the image formed by Mirror B of a point on the SLM is as far above the center of curvature image as the object is below the center of curvature point.

The behavior in the x direction is identical with the exception that Mirror B is tipped ony in the y direction so that [theta] = 0. The x equation equivalent is x[2] = - x[1]. Since the center of curvature point is on the y axis, an image of a point source from the center of curvature is as far from the source point as the object was, but on the opposite side in both the x and y directions. To find the image of a point source on the SLM, one can merely reflect about the center of curvature point.

Increased Delay Time Due to Glass Blocks. Here is presented an analysis of a dual cell with auxiliary mirrors with glass blocks in front of Auxiliary Mirror I. The situation analyzed is shown in FIG. 5a. The SLM 12 is shown, along with a polarizing beam splitter 28, lens f227, the White cell mirrors (13, 14, 24, 25) and Auxiliary Mirror I 29 and a group of glass blocks 30. The size of the polarizing beamsplitter is d[1]and its refractive index is n[1]. The focal length of cell lens f2 is f[2]and is separated from the White cell mirror by a distance d[EF]. The distance, d[2], between lens f1 and Auxiliary Mirror I is divided into two regions, one of thickness d"[2]filled with air or other material, and the other of thickness d'[2]filled with material of refractive index n[2].

It is chosen that f[2] = d[EF]. The requirement that the SLM be imaged onto Auxiliary Mirror I can be easily calculated. The result is d'[2]/n[2] + d"[2] = 2d - d<2>[EF]/f - d[1]/n[1]. It can be noted that d"[2] = 0 and d[2] = d'[2] = d[1], d[EF] = D, and n[2] = n[1]the equation reduces nicely, giving the desired combinations of d'[2]and d"[2]that will give imaging. The distances d'[2]and d"[2]must further be reduced to the transit time. The transit time, T[1], for one pass from the SLM to Auxiliary Mirror I and back is given by cT[1]/2 = n[1]d[1] + 2d + n'[2]d'[2] + d"[2]. This can be rewritten to give a second equation involving d'[2]and d"[2], n[2]d'[2] + d"[2] = (cT[1]/2) - n[1]d[1] - 2d[EF]. From these equations there is an allowed range for the variables d'[2]and d"[2]and T[1]. A plot of d"[2]versus d'[2](shown in FIG. 13) can be created showing the region of interest, where d'[2]and d"[2]are positive. It could then be noted that the slope of the first equation is - 1/n[2]and the intercepts that depend on d[2], f, d[1], and n[1]are also fixed. The slope of the second equation is - n[2](constant) and the intercepts depend on T[1], which is variable. The line shifts to the right as T[1]increases. The minimum value of T[1]occurs when the two lines intersect on the vertical axis, i.e. T[1,min] = (2/c)[n[1]d[1] + 2d[EF] + (2d[EF] - [d<2>[EF]/f] - [d[1]/n[1]])]. There is a minimum value for d[2]. The line representing the distance d[2], d'[2] + d"[2] = d[2], can be plotted, from the lens f1 to the Auxiliary Mirror I. This line also moves to the right as d[2]increases. The smallest value of d[2]occurs when the lines intersect on the vertical axis. That gives the minimum distance from the lens f1 to Auxiliary Mirror I, d[2,min] = 2d[EF] - (d<2>[EF]/f) - (d[1]/n[1]).

Combining equations to solve for the thickness of the glass and of the air, these expressions are most easily written if 2d[EF] - (d<2>[EF]/2f) - (d[1]/n[1]) is replaced in terms of d[2,min]and if n[1]d[1] + 2d is replaced in terms of T[1,min]: ' [][[] []] []" [][[] []] [] <=22> Get Mathematical Equation

This gives the incremental thickness of the glass, d'[2], that will give an incremental time increase, T[1] - T[1,min]. An expression for the full distance d[2], from lens f1 to Auxiliary Mirror I can be obtained by combining these equations: d[2] = d[2,min] + [1/(n[2] + 1)](c/2)(T[1] - T[1,min]). This starts at d[2,min]as expected and increases with (T[1] - T[1,min]). Distance d[2]can also divided into d'[2]and d"[2]. As the time delay increases the position of the reflecting surface moves back, the glass becomes thicker and the air layer thinner. For that refractive index, the air layer is decreasing twice as fast A) as the auxiliary mirror is moving back. The size of various parameters can also be estimated for a typical situation. One can choose d = f1 = 40 cm, f = 50 cm, d[1] = 3.81 cm(1.5 in), and n[1] = 1.5. d[min] = 61.46 cm, T[min] = 9.58 nanoseconds, and [DELTA] d'[2]/ [DELTA] T[1] = 1.8 x 10<11> mm/sec. Thus, if a

delay of 10< - 12> seconds is desired, a block 0.18 mm thick can be used.

Deformable Mirror Device SLM. To derive a ray matrix for a particular situation two equations are needed, one showing how the distance of a ray from the axis changes as the ray moves through the object, and the other showing how the ray slope changes. Some pixel-mirrors of the DMD are oriented with their normals at + [theta] and some at - [theta] , as shown in FIG. 14a, where for one device [theta] = 10 [degrees] . The surface of the DMD may be defined as a vertical line (y direction) intersecting the center of each pixel so that part of the pixel is behind the surface and part is in front of it. A ray can enter from the right with an angle p[o], as shown in FIG. 14b, and intersects the pixel at a distance y above the center of the pixel and is reflected off the pixel. At the point the ray intersects the pixel it is a distance - y tan [theta] behind the surface. In going from the surface to the pixel, the height of the ray has increased a distance d tan p[o], = y tan [theta] tan p[o]. After reflection from the pixel the ray again passes through the surface. In doing so the height has further increased a height d tan(p[o] + 2 [theta]) = y tan [theta] tan(p[o] + 2 [theta]). The height has changed by a total distance [DELTA] y = y tan [theta] [tan(p[o]) + tan(p[o] + 2 [theta])].

The ray matrices deal with paraxial rays so that p[o] < < [pi] , and [theta] = 10 [degrees] < < 180 [degrees] , also a small angle. Putting the tangent of the angle equal to the angle, the increase in height [DELTA] y = 2y [theta] ([theta] + p[o]). The net result of all these steps is that the increase in height is proportional to the product of small angles and can be neglected. Thus the first matrix ray equation relates the input y value, y[o], with the output y value, y[1], as y[1] = y[o]. The second equation is the one for the slopes. Using the law of reflection, the incident slope, p[o], and the reflected slope, p[2], are related as p[1] - [theta] = p[o] + [theta] , or p[1] + p[o] + [theta] . Combining these equations into a 3 x 3 ray matrix yields the ray matrix for the DMD: [theta] <=23> Get Mathematical Equation

There is an addendum that can be mentioned, where the discussion could also apply to reflection off a tipped plane mirror if extending the edge of the pixel-mirror. Thus, the matrix equation also applies to a tipped plane mirror if the tip angle is small. If the tip angle is not a small angle, however, then the approximation does not hold and there will be an increase in distance from the axis.

Next, a prism with a small angle is considered, as shown in FIG. 15. A prism with its apex pointing down can be considered. The refractive index of the prism material is n. The two large sides make small angles [alpha] [o]and [alpha] [1], with the vertical. A ray with slope p[o]and height y[o]can come in from the right, be refracted at the interfaces, and leave. Since the angles between the surfaces and the vertical are small, arguments like those used previously for the mirror can be used to show that the vertical displacement in crossing the prism can be neglected. The first matrix equation is then y[1] = y[o]. Snell's law can be used to derive the equation for the change of it slope. The entering ray has a slope p[o]. The slope of the ray exiting the surface is p'. The angle between the ray entering the surface and the normal is p[o] - [alpha] [0]. Similarly, the angle between the ray exiting the surface and the normal is p' - [alpha] . Snell's law is then sin(p[o] - [alpha] [o]) = n sin(p' - [alpha] [o]), or using the small angle restriction, np' = p[o] + 2(n - 1) [alpha] [o]. A comparable equation can be written for the ray as it exits the left-hand surface: p[2] = np' + (1 - n) [alpha] [1].

Eliminating p' and defining the prism angle, [alpha] = [alpha] [o] - [alpha] [1], we have the equation for the change of slope by the prism, p[2] = p[1] + (n - 1) [alpha] . The ray matrix for the small angle prism is then: [alpha] <=24> Get Mathematical Equation

Discussion

A dual White cell is shown in FIG. 3 connected by a polarizing prism beamsplitter. The mirror in the optical spatial light modulator 12 and spherical mirrors B 13 and C 14, combined with lens f127, constitute one White cell, hereafter referred to as Cell I. The mirror in the SLM and spherical Mirrors E 24 and F 25, combined with lens f226, constitute a second White cell called Cell II. The distances between the SLM and Mirrors B and C are the same, and the distances for light reflected off the polarizing beamsplitter going to Mirrors E and F are the same. The distance from the SLM to Mirrors E and F is greater than the distance from the SLM to Mirrors B and C. In operation, a light beam bounces from the SLM to one of Mirrors B, C, E and F and back again on each traverse of the cell.

The polarizing beamsplitter and the SLM determine which cell the beam goes to on each pass. The polarizing beam splitter transmits light of one polarization, say the plane of the figure, and reflects light of the polarization perpendicular to the plane of the figure. If the light starts out going to Mirror B with polarization in the plane of the figure and the SLM does not change the polarization, it is then reflected back and forth between the SLM and Mirrors B and C. Conversely, if the light starts towards Mirror E with polarization perpendicular to the plane of the figure and the SLM does not change the polarization, it will continue to reflect between the SLM and Mirrors E and F. The path of a beam can be changed from one cell to the other by using the SLM to rotate the plane of polarization as the beam bounces off the SLM.

The present disclosure discusses a set five possible imaging conditions. First, the focal length of lens f1 is chosen to image Mirror B onto Mirror C and vice versa. Second, similar to the first condition, the focal length of lens f2 is chosen to image Mirror E onto Mirror F and vice versa. This requirement may be met by placing Mirrors B and C in the right hand focal plane of lens f1 and by placing Mirrors E and F in the focal plane of lens f2. The third condition is that Mirror B should be imaged onto Mirror F, and Mirror C should be imaged onto Mirror E. The requirement that Mirrors B and C be in the focal plane of lens f1 together with the requirement that Mirrors E and F be in the focal plane of lens f2 also satisfies this condition.

The last two imaging conditions are also comparable. The fourth condition is that the focal lengths of Mirrors B and C are chosen so that, in conjunction with lens f1, Mirrors B and C image a small spot of light on the SLM back onto another small spot on the SLM. The last condition is that the focal lengths of Mirrors E and F are chosen so that, in conjunction with lens f2, a small spot of light on the SLM is again imaged back onto the SLM.

In operation, a point of light starts on a small mirror next to the SLM called a turning mirror. The light is directed towards Mirror B. Suppose the light is polarized in the plane of the figure so that it is not reflected off the polarizing beam splitter. Mirror B images the spot light onto the SLM. In one scenario, the light is reflected off the SLM and imaged by lens f1 onto Mirror C, which images it to a different spot on the SLM. It then goes to

mirror B, which again images it onto the SLM. The light bouncing back and forth forms a sequence of spots on the SLM.

If the polarization is changed by the SLM to be perpendicular to the plane of the figure, the light bounces in a similar fashion back and forth between Mirrors E and F and the SLM. The plane of polarization of the light can be changed at any bounce off the SLM so that any combination of paths in cells one and two can be chosen. The quantity of interest, the transit time through the cell, is the number of bounces off Mirrors B and C times the transit time from the SLM to Mirror B and back, plus the number of bounces off Mirrors E and F times the transit time from the SLM to Mirror E.

Considering the exact locations of the spots of light on the SLM, there are various configurations depending on the locations of the centers of curvature of Mirrors B, C, E and F, and also depending on the spot size relative to the size of the SLM. The centers of curvature of Mirrors E and F are superimposed on those of Mirrors B and C so that the spots from cell E-F are also coincident with those from cell B-C. Reference will only be made to the centers of curvature of Mirrors B and C for simplicity.

FIG. 2 is a view of the SLM looking from lens f1, showing the most traditional spot configuration. The SLM is assumed to have a square shape. Also shown are two long thin mirrors, the input and output turning mirrors respectively below and above the SLM. For this case, the turning mirrors are centered at distances of +/- 2m [delta] where m is an integer related to the number of times the light is re-imaged onto the SLM and the SLM is taken to have dimension 2(2m - 1) [delta] on a side and [delta] is the distance below and above the optical axis, respectively, of the projections of the centers of curvature of Mirrors B and C.

Imagine a point of light on the right end of the input turning mirror, as shown in FIG. 16a, conditioned, as mentioned previously, to be traveling toward Mirror B. That spot is imaged to a new point on the SLM located opposite the center of curvature of Mirror B and an equal distance from the center of curvature. The position of the input spot on the turning mirror is (x[o], y[o]), where y[o] = - 2m [delta] . The point image is at a location opposite the center of curvature of Mirror B. To find that location the sign of the coordinates is reversed and 2 [delta] is subtracted because the center of curvature of Mirror B is below the axis. If the light were being imaged by Mirror C, the sign of the coordinates would be reversed and 2 [delta] added. The result is

(x[1], y[1]) = (- x[o], - y[o] - 2 [delta]) = (- x[o], + 2 [delta] (m - 1)).

The light is then reflected back and re-imaged by Mirror C. The point image is opposite the center of curvature of Mirror C and an equal distance from it. The location is then at (x[2], y[2]) = (- x[o], - y[o], + 4 [delta]) = (x[o], - 2 [delta] (m - 2)). As the process continues, the light alternatively bounces off Mirrors B and C and is re-imaged. Locations of successive spots are designated as (x[n], x[n]) at the n-th re-imaging. These spot locations are given by

(x[n], x[n]) = ((- 1)<n>x[o],(- 1)<n>(y[o] - 2n [delta])) = ((- 1)<n>x[o],(- 1)<n>2(m - n) [delta]).

Imagine a set of points for m = 3, as shown in FIG. 16b. The point images can be indicated with "x"'s. The images form two vertical lines at +/- x[o]. The horizontal coordinate of the points alternates to the right and left of center. As the image number n increases, the spots also alternate above and below the axis first moving successively towards the axis for n = 1,2, and 3, and then away from the axis for n = 4, 5, and 6. The process ends when n = 2m = 6 and the imaged spot winds up on the output turning mirror at the top. There are 2m - 1 = 5 point images on the SLM.

There may be gaps between "x" spots in the columns on both sides. These can be filled by placing a second input spot at (- x[o], y[o]). More spots can be added on the input turning mirror, as shown in FIG. 16c, at different values of x[o]. A complete line of spots then results on the input turning mirror, the spots being paired at different values of +/- x[o]. Columns of spots can fill the area of the SLM.

Instead of a specific situation where the centers of curvature of mirrors B and C are equidistant from the optical axis, a more general situation can be discussed. There, the centers of curvature of the mirrors are shown on the y-axis. The center of curvature of Mirror B is at location y[B]. The center of curvature of Mirror C is a distance 2 [delta] above it. The input spot is at location x[o], y[o], The expression for the location of spot n is (x[n], y[n]) = ((- 1)<n>x[o],(y[B] + [delta]) + (- 1)<n>(y[o] + 2 [delta] n)), where y[B] + [delta] is the location of the point midway between the two centers of curvature. The equation still gives two columns of spots parallel to the line between the centers of curvature, the y-axis. The spots alternate from one column to the other as n increases. In general, a distance 4 [delta] separates the spots in a given column. The vertical positions of the spots in one column are, however, not identical with those in the other column. They depend on the y value of the location of the input spot. The equation reduces to the previous equation when y[B] = - [delta] . Two special cases of present themselves. For simplicity, the origin is taken midway between the centers of curvature so that y[B] + [delta] = 0. In the first case y[o]is an even integer times [delta] , or y[o] = n[e] [delta] (n[e]even). This is the situation for n = 6. Then the y values of the spots in one column are midway between the y values of the spots in the other column. The input spot is on the bottom turning mirror and the output spot is on the top turning mirror. There are m - 1 reflections off the SLM.

The second specific case arises when y[o]is an odd multiple of [delta] , y[o] = n[o] [delta] (n[o]odd). Then for each spot in one column there is a spot opposite it in the other column. The input spot is on the bottom turning mirror and so is the output spot. There are still n - 1 spots on the SLM. This situation can be illustrated for n = 5 in FIG. 17. It is possible to fill in the gaps between the spots in the two columns. That can be accomplished by putting an input spot on the top turning mirror at location (x[o], - y[o]) with light directed towards Mirror C. For both configurations one can fill the SLM with spots by using many spots on the turning mirrors.

Generally, it is desired to have the spots close together to utilize the SLM area in an optimum fashion. If the SLM is divided into independent areas called pixels then it would be preferred to have one spot per pixel. Let the spot size be [sigma] . Since the spots are separated by a vertical distance of 2 [delta] , it may be preferred that [sigma] = 2 [delta] , i.e. the distance between the centers of curvature of mirrors B and C should be equal to the spot size. The

spots may also be separated by a distance 2 [delta] in the horizontal direction.

The number of bounces on the SLM was taken to be equal to the number of spots from top to bottom on the SLM. This may well not be the case. In many situations the number of spots from top to bottom on the SLM may be of the order of many hundreds but on[1]y tens of bounces may be desired. In that case, groups of spots can bounce back and forth in synchronization. Two examples can be considered. There can be sets of spots arranged in columns being reflected, or other array of spots being reflected. In both cases the set of spots can be reflected five times off the SLM. The use of spot arrays allows one to make most effective use of the SLM capabilities.

The time delays possible with the dual cell are also considered. As described, there are a number of beams, each executing n bounces. Each beam can go to either Cell I, which includes Mirrors B or C, or go to Cell II, i.e. Mirrors E or F. To derive the expression for the time delays, D[BC]is defined to be the optical distance in Cell I, i.e. from the SLM to Mirror B or C and back. D[EF]is defined to be the optical distance in Cell II, i.e., from the SLM to Mirror E or F and back. d[BC]is the distance from the cell lens to either Mirror B or Mirror C, and the corresponding distance in to Mirrors E and F to be d[EF].

D[BC] = 2n[1]d[1] + 2d[BC]

D[EF] = 2n[1]d[1] + 2 d[EF]

Here, n[1]and d[1]are the refractive index and size of the prism respectively. As before, the light leaving the SLM can be controlled by the polarization change at each pixel to go to either cell. If there are k = n - 1 total bounces off the SLM and i of these bounces go to Cell II, then k - i bounces go to Cell I. The total time delay, T, is given by T = (1/c)((k - i)D[BC] + iD[EF]) = (1/c)(kD[BC] + i(D[EF] - D[BC])). There are three items of interest in this equation. The equation has two terms. The first term is proportional to m and is constant. Thus there is always a constant time delay, T[C] = (1/c) mD[BC]in this device. The second term is proportional to i and is variable. This controlled incremental part, T[1], proportional to i, is added to the constant part, giving T[1] = + (i/c)(D[EF] - D[BC]). Increasing i by one unit increases the transit time by an increment, [DELTA] T given by [DELTA] T = (1/c)(D[EF] - D[BC]). Thus the time delay increment, [DELTA] T, is given by the path difference between Cell II and Cell I. This can be made to take on a wide range of values.

The time increment, [DELTA] T, can be expressed in terms of design parameters, d[BC], d[EF], f[1], and f[2]. D[BC]and D[EF]can be replaced using previous equations. d[1]can then be eliminated in each cell using a previous imaging condition, written with d replaced by d[BC]for Cell I and by d[EF]for cell II. The result is

[DELTA] T = [2(n[1]<2> + 1)(d[BC] - d[EF]) + 2n[1]<2>([d<2>[BC]/2f[1]] - [d<2>[EF]/2f[2]])]

This reduces as expected. If d[BC] => d[EF]and f[1] => f[2]then Cell I becomes identical with Cell II and [DELTA] T => 0. There are k possible values for i, so there are k possible time delays and the maximum incremental delay, T[1,max]given by T[1,max] = k [DELTA] T. Thus the maximum incremental delay

is proportional to the maximum number of bounces. This is improved in other designs of the present disclosure.

The dual arm cell can again be extended. As before, the distances d[BC]and d[EF]to the pairs of White Cell mirrors are made unequal. The optical distance from the SLM to Mirror F is made greater than that from the SLM to Mirror E. These have the advantage of increased flexibility in the choice of possible delays. The number of possible delays will go as k<2> where k is the number of bounces off the SLM.

FIG. 4 is identical to the configuration of FIG. 3 with the exception that Mirror F has been replaced with Lenses G125c and G225b and Mirror G325a. Of these, Lens G1. is chosen so that, in conjunction with Lens F2, the SLM is imaged onto Lens G2. Thus, Lens G2 is conjugate with the SLM. Lens G2 is chosen to image the plane of Lens G1 onto Mirror G3 with unit magnification, so that Mirror G3 is conjugate with the plane of Mirror G1, which is also conjugate to Mirror E. Mirror G3 is chosen to have its center of curvature on Lens G2. The image of its center of curvature then also lies on the SLM, and is located so that the spots bounce as mentioned previously. The imaging conditions of the dual arm cell are still satisfied. An alternative configuration with lenses G1 and G2 replaced by mirrors is also included in the present disclosure. Further, G1 and G2 may be combined into a single lens.

One main improvement comes from the different transit time for light in the arm containing Lenses G1 and .G2 and Mirror G3. In addition to D[BC]and D[EF]there is a new distance, the optical distance D[EG]from the SLM to Mirror G3 and back where D[EG] = 2n[1]d[1] + 2d[EG], n[1]and d[1]being the refractive index and size of the prism as defined previously. Then d[EG]can be written in terms of f[G3]the focal length of Mirror G3 as d[EG] = d[EF] + 2f[G3]. A configuration then exists with the optical distances from the SLM to Mirrors B and C equal but the distances from the SLM to Mirrors E and G unequal. To proceed, it is necessary to know the number of bounces a given spot will make off the SLM. As before, the number of bounces is designated n, and for the sake of discussion it is assumed there are an even number of bounces. The difference in transit times between the SLM and Mirrors B or C and Mirror E is then set equal to the smallest desired time increment, [DELTA] T. The difference in transit times between Mirrors B or C and Mirror G3 is set to ((n/2) + 1) [DELTA] T, where [DELTA] T = (1/c)(D[EG] - D[BC]). These times are accomplished by choice of focal lengths for the various elements. The reason for these choices will be made apparent. Since [DELTA] T is a difference in lengths, it can be made quite small.

In examining the possible sequences of bounces on the SLM, it can be assumed that the spot starts on the turning mirror next to the SLM and goes first to Mirror B and back to the SLM. From the SLM there are two choices, towards either Mirror C or Mirror G, depending on the polarization of the light leaving the SLM. Upon return the light can either go to Mirror B or Mirror E. After odd-numbered bounces off the SLM, the light can go to either Mirrors C or G. After even-numbered bounces off the SLM, the light can go to either Mirrors B or E. The light bounces half the time off Mirrors B or E and half the time off Mirrors C or G. The shortest transit time occurs when the light always goes to Mirrors B and C and the longest transit time occurs when the light always goes to Mirrors E and G.

The transit time for a given sequence of bounces can then be expressed by letting i be the number of bounces off Mirror E and j be the number of bounces off Mirror G. 0 [less than or equal to] i,j [less than or equal to] (n/2). Then the number of bounces off Mirrors B and C will be ((n/2) - i) and ((n/2) - j) respectively. The transit time for the n bounces going i times to Mirror E and j times to Mirror F, T(ij), is given by [] [] <=25> Get Mathematical Equation

Or, using previous expressions, T(i,j) = T[o] + [DELTA] T (i + j ((n/2) + 1)) where T[o] = (n/c)D[BC]. The first term, T[o], is a constant and represents a base minimum delay. It occurs when i = j = 0. The progression of increasing delays is now shown. After i = 0, the next delay occurs when i = 1,j = 0. i can continue to be incremented until i = (n/2). Then set i = 0, j = 1 and start incrementing i again. This is identical to a radix system of base (n/2). The longest delay occurs when i = j = (n/2). It is T[(n/2), (n/2)] = [DELTA] T[(n/2)<2> + 2(n/2)]. As predicted, the maximum n is proportional to n<2>.

A configuration that is optically identical to the previous configuration can be imagined, having Lenses G1 and G2 replaced with spherical mirrors F1 and F2. As before, Mirror F1, in conjunction with lens F2, images the SLM onto Mirror F2. Mirror F2 then images Mirror F1 onto Mirror G3. Finally, the center of curvature of Mirror G3 is centered on Mirror F2

The design of the dual armed TTD unit can additionally be modified to improve the number of potential time delays, where the number of delays can be proportional to 2<n> rather than to n<2>. The modification can be done in two parts: first by adding Auxiliary mirrors in the plane of the SLM, and then adding time delay mechanisms in conjunction with the auxiliary mirrors. The dual cell with auxiliary mirror is shown in FIG. 5 as a three-dimensional rendition of the dual cell. Added to it are two mirrors, one over the SLM called Auxiliary Mirror I, and an extra mirror or other reflective material over the edge of the beam-splitting cube, called Auxiliary Mirror II. The optical axis is between the SLM and Auxiliary Mirror I. Lens f1 has been made larger to cover the SLM and Auxiliary Mirror I. The turning mirrors are at the left of Auxiliary Mirror I and the SLM.

The operation is comparable to that of the dual cell with the plane of the SLM enlarged. The light starts on the Input Turning Mirror and goes first to Cell I. Mirrors B and C image the Input Turning Mirror spot onto the SLM. If the SLM does not change the polarization the light is imaged onto Auxiliary Mirror I and again onto the SLM. If the SLM changes the polarization, the light that is reflected off the beam-splitting cube is imaged onto Auxiliary Mirror 11. Light leaving Auxiliary Mirror II is similarly re-imaged back onto the SLM. Lens f1 images Mirror B onto Mirror C and lens f2 images Mirror E onto Mirror F, as before. Other configurations satisfying the same requirements but having various advantages are also presented in the present disclosure.

The number of bounces on the SLM, m, is chosen to be equal to the number of bits of time delay required. For example if two hundred different time delays are desired, that would require eight bits, m = 8, requiring eight bounces on the SLM. The SLM surface is then divided into m areas such that each beam falls once into each area. Thirty-six input spots are shown on the turning mirror in FIG. 18. Only the images associated with the upper left hand turning mirror spot are shown on the SLM and Auxiliary Mirror for simplicity.

The length of the path traveled by the beam can be changed in Cell II on the traverse in which it strikes each of the different areas. To discuss this approach, suppose Mirrors B and C are taken the same distance from the SLM as Mirrors E and F. Extra path length can be placed in front of or in place of each area of Auxiliary Mirror II. The methods of increasing the path length will be presented shortly. The distance associated with the increase in path length is chosen to be a binary function of some minimum distance, [DELTA] L, and [DELTA] T is the minimum non-zero time delay. The relationship is given by [DELTA] T = (2n[1]/c) [DELTA] L, where n[i]is the refractive index of the material in which the light probagates and c is the speed of light in vacuum. Thus the incremental time increase associated with first area on Auxiliary Mirror II is [DELTA] T, that with the second area is 2 [DELTA] T, that with the third area is 4 [DELTA] T, etc. The general expression for the time delay with this approach is T = 2mD[BC] + [DELTA] T([delta] [1] + 2 [delta] [1] + 4 [delta] [3] + . . . + 2<(m - 1)> [delta] [m]) where the [delta] [1]describe whether the i-th delay is added in. If [delta] [i] = 0, light goes to Auxiliary Mirror I, if [delta] [i] = 1 then light goes to Auxiliary Mirror II. There is a constant delay, T[C] = 2mD[BC]. The factor of two in front of D[BC]occurs because the distance from the SLM to Auxiliary Mirror I and back required for this case is twice the distance from the SLM to Mirror B or Mirror C and back as required for the Dual Arm cell. There is also an incremental delay, T[1] = 2 [DELTA] T ([delta] [1] + 2 [delta] [1] + 4 [delta] [3] + . . . + 2<(m - 1)> [delta] [m]). The maximum incremental delay, T[1,max]is given by T[1,max] = [DELTA] T(2<m> - 1). This is a considerable improvement. The incremental length, [DELTA] L can be implemented in many ways. For small time increments, blocks of material such as glass can be added next to the auxiliary mirror. For larger time increments an optical transmission line of the desired length may be added.

The method of adding blocks of glass or other transparent material is shown in FIG. 5a, where blocks of glass of different thickness are shown. The blocks are oriented to replace Auxiliary Mirror II. The thickness of the blocks are chosen so that the additional time required for the beams to go through successive blocks increases as powers of two times the initial thickness. In operation, the light in a given beam goes either to each section of Auxiliary Mirror II and receives the associated delay, or goes to Auxiliary Mirror I and receives no delay. For example, on a particular pass through the cell suppose the beam's polarization is such that it passes through the beamsplitter. This beam goes to Mirror B or C, from which it goes to Auxiliary Mirror I, encounters no glass blocks, and receives no delay. If on that pass the beam's polarization has been changed, the beam goes to Mirrors E or F and thence to Auxiliary Mirror II where it passes through the associated extra optical distance of the glass block.

As before, d[1]and n[1], are the thickness and refractive index of the beamsplitting prism. Let f be the focal length of the White cell mirrors, and let d be the distance from lens f2 to the White cell mirrors E and F, as well as to mirrors B and C. The focal length f1 of cell lens f2 is set equal to d[EF]. The distance d[2]from lens f1 to Auxiliary Mirror II is divided into two parts, d'[2]filled with glass of refractive index n[2], and d"[2], filled with air. This corresponds to a representative block of glass.

The expressions for the thickness of the air, d"[2]and thickness of the glass, d'[2]are given in terms of two parameters, the minimum distance between the lens and Auxiliary Mirror I d[2,min]and the minimum transit time, T[min], from the SLM to Auxiliary Mirror I. They are d[2,min] = 2d[EF] - (d<2>[EF]/f)

- (d[1]/n[1]), which reduces to the single cell imaging case if the material along distance d[2]is changed to glass of index n[1]and d[2] => d[1]. For that case there is a minimum transit time from the SLM to Auxiliary Mirror I and back. It is T[min] = (2/c)(n[1]d[1] + 2d[EF] + d[2,min]) = (2/c)(n[1]d[1] + 2d[EF] + (2d[EF] - (d<2>[EF]/f) - (d[1]/n[1])). Both the minimum distance and the minimum transit time occur if there is no glass, d'[2] = 0.

Then in terms of these parameters the thickness d'[2]of a glass block required for incremental time delay T[1] - T[1,min]is given by d'[2] = [n[2]/(n[2]<2> - 1)](c/2)(T[1] - T[1,min]), and the total distance, d[2], from lens f1 to Auxiliary Mirror I is given by d[2] = d[2,min] + [1/(n[2] + 1)](c/2)(T[1] - T[1,min]). By setting (T[1] - T[1,min]) = 2<(i - 1)> [DELTA] T, these equations can then be used to calculate the thickness of the i<th> block. Alternatively, if all the dimensions are known, then the transit time can be calculated as [DELTA] T = [2(n[2] + 1)/c](d[2] - d[2,min]). This is comparable to the previous equation for the dual cell. The approach using a glass block is good for very small delays. If the blocks get too long then the beams start to broaden and are vignetted by the edge of the block. In that case other approaches may be used.

One approach would be to use an array of optical fibers in place of the glass blocks.

The lens transmission line provides another method of generating time delays that may be appropriate when the delays are much longer than those allowed by the glass block method. The situation is shown in FIG. 9. There are five lens groups labeled 43a, 43b, 43c, 43d, and 43e, each group comprising three lenses. The plane on the right 44 is the input or object plane and is intended to be coincident with and replace the plane of Auxiliary Mirror II. Light that was reflected off Auxiliary Mirror II now proceeds to the left into the lens system. There are five planes conjugate to the plane of Auxiliary mirror II, labeled 45a, 45b, 45c, 45d, and 45e, lying at the junctions of the five lens groups. FIG. 10 shows the plane of Auxiliary Mirror II and the five conjugate planes in three dimensions. As all the groups may operate identically, only one group will be considered. Recall that at the input to a group and the output to a group there is a plane conjugate to Auxiliary Mirror II (and therefore to the SLM). There are three imaging tasks performed by a group. The first task is basic to the operation and will be considered immediately. The other two tasks deal with light conservation.

The first possible task of a lens group is to image the input conjugate plane onto the output conjugate plane. The lens in the center performs that operation. The focal length of the lens, f, can be separated from both conjugate planes by a distance 2f. This can produce the desired imaging. The input and output conjugate planes are related by a magnification of - 1.

In operation, a portion of the areas of each conjugate plane are replaced by vertical strip mirrors. These areas correspond to the areas of the glass blocks in the previous design. This is seen in FIG. 11 where the shaded areas correspond to the mirrors. Light incident in Area I of the plane of Auxiliary Mirror II passes through it and Group G1, and is reflected at conjugate plane 45a by the vertical strip mirror placed to cover the image of Area 1. Light passing through Area II of the plane of Auxiliary Mirror II passes through Lens Groups 43a and 43b, and is reflected by a mirror placed in Conjugate Plane 45b at the image of Area II. Similarly, light in areas III, IV, and V is reflected

by mirrors strategically placed in Conjugate Planes 45c, 45d, and 45e.

The length of the lens groups determines the time delays. The length of the first lens group may be chosen so that the light that travels through Lens Group 1, reflects from the strip mirror in Conjugate Plane 45a, and travels back has the shortest desired time, [DELTA] T. The length of the second group is equal to that of the first group so that the transit time through groups 43a and 43b and back is 2 [DELTA] T. The length of each successive group is then made equal to the sum of the lengths of the preceding groups. The length of group 43c is made equal to the sum of the lengths groups 43a and 43b. The transit time then up through Group 43c up to Conjugate Plane 45c and back is 4 [DELTA] T as desired. The remaining lengths are chosen accordingly so that light passing up through Group m to Conjugate Plane m and back has a time delay 2<(m - 1)> [DELTA] T.

Returning to the other two tasks performed by the lens groups, the second task involves conserving optical throughput. There have been situations where it was be desired to put a plane mirror in the conjugate plane next to the left-hand lens of the group to reflect light back through the system. It will be desirable to have all the light that comes through the center-imaging lens to go back through that lens. To accomplish this, the left-hand lens in each group is chosen so that when the plane mirror is placed next to it, it then images the center lens onto itself. This may be accomplished by letting the focal length of the left-hand lens be equal to the distance of that lens from the center lens. The lens and plane mirror combination will have a focal length of half the center-to-left hand lens distance and there is a magnification of - 1 so that the edges of the center lens are indeed imaged onto themselves. Another way of considering the operation of the left-hand lens arises because its focal point is on the center-imaging lens. The left-hand lens collimates light leaving any point on the center-imaging lens. It is still collimated after being reflected by the plane mirror so upon return it is refocused by the left-hand lens back onto the center-imaging lens. The left-hand lens is in actuality a field lens placed next to the output conjugate plane. Since it is next to the conjugate plane it does not affect the imaging of the center lens onto that plane.

The third task performed by a lens group is again devoted to conserving light. It is to assure that all the light entering the center imaging lens of one group left the center imaging lens of the proceeding group. To do this, the center lens of one group can be made the image of the center lens of the proceeding lens. This can be accomplished by properly choosing the right hand lens of the group so that, when combined with the left-hand lens of the preceding group, the desired imaging is produced. This can be accomplished by making the focal length of the right hand lens equal to the distance between the right hand lens and the center lens, so that the focal point of the right hand lens is on the center lens. Light leaving a point on the center lens of one group is then collimated by the left hand lens and refocused by the right hand lens of the next group onto the center imaging lens of the next group. There is one minor exception: the first lens in the first group images Mirrors E or F onto the central imaging lens of the first group. With these three imaging conditions, a given conjugate plane is imaged onto the next conjugate plane and no light is lost through aperturing of the center imaging lenses. The process can be extended if more delays are desired with more groups and more areas on Auxiliary Mirror II and its conjugate planes.

In a system of lens groups, alternatively known as a lens train', the segmented mirrors can optionally be replaced with gratings that reflect one

wavelength and pass all others, such as a Bragg grating. Then for a beam bouncing through the White cell, the delay it experiences would depend on its wavelength. One could use a tunable laser to program in the delay by changing the wavelength of the device. Such a cell would not require a spatial light modulator or a dual White cell, just a single White cell with the lens train in place of Mirror A, where the SLM used to be.

There are other approaches that use tunable lasers to map delay to wavelength. In one such approach light is projected down a fiber containing Bragg gratings tuned for different wavelengths. Depending on the wavelength of the beam at any instant, the light travels down the fiber a different distance to the correct wavelength-specific grating, passing through all the other gratings, and gets reflected back. A tunable laser or wavelength-altering element may be required for each antenna element in this approach.

A Deformable Mirror Device spatial light modulator (DMD) is also used in the present invention. The DMD has the potential advantages of higher'information density and faster speed. But it also has some associated problems that have to be addressed. The DMD is a pixilated spatial light modulator. That is, the reflecting surface is divided into incremental image areas. Each image element has a mirror surface that can be independently rotated to two positions, for example making angles of +/- 10 [degrees] with the surface. The elements can modulate the direction of the reflected light by changing the input direction to one of two output directions. It does this by individual image element. The direction change can be transformed into an amplitude change by directing the reflected light through an aperture or directing it to something blocking it. Pulsing the mirror between transmitting and blocked states, at a rate faster than eye response, can also change the average observed amplitude.

Imagine a cut through the DMD surface, where the individual mirrored image elements are shown. Some are rotated in one direction, the remaining mirror elements in the other possible direction. The angle, [theta] , of tip is +/- 10 [degrees] on presently available devices so that light incident normal to the plane of the DMD is reflected from a given image element at +/- 20 [degrees] . The reflective image elements or pixels are currently square, 16 [mu] m on a side with a spacing of 17 [mu] m between centers. There is a hole in the center of each image element roughly 6 [mu] m in diameter. The pixels rotate about a diagonal. The light incident perpendicular to the paper is reflected in the +/- x direction.

The DMD presents an interesting pattern on reflection. To see this, compare it to a flat mirror 47 as shown in FIG. 19a. The intersection of the mirror surface with the x-z plane makes an angle [alpha] with the x-axis. A plane wave travelling in the z direction enters at the bottom, is reflected off the mirror, and exits to the lower left. This is in the near field of the mirror. A continuous reflected wavefront results as expected. Considering a plane wave reflected off the DMD 48, as shown in FIG. 19b, the image element mirror surfaces are all oriented in the same direction for simplicity. The mirror surfaces do not form a continuous surface as in the case of the extended plane mirror. As a result the field reflected off the DMD is a discontinuous set of wavefronts all travelling in the same direction but with some lagging behind. The discontinuous set forms an "average" plane parallel to the plane of the DMD. However, this average plane is not perpendicular to the direction of propagation of the reflected light.

The fact that the elements of the DMD do not lie in one continuous surface makes it more difficult at times to image the DMD in reflected light. The difficulty is shown in FIG. 20a. A DMD 49 at the left is normally illuminated with a beam from the right. The reflected light is imaged with a lens 50. Neither the object plane nor the image plane is perpendicular to the direction of propagation of the light leaving the DMD. Indeed the object plane and image plane are parallel only if the magnification is unity or if the lens is rotated to be parallel to the object plane. The main problem is that the object and image planes are not perpendicular to the direction of propagation.

If the direction of the light were reversed so as to be incident on the DMD 49 at an angle and leaving it perpendicular to the surface, as shown in FIG. 20b, then there would be no problem. That is the way projectors using the DMD operate. For application in a White cell, however, it may be necessary to have light approaching the SLM from both directions.

One way to remedy the problem of the object plane and image plane not being perpendicular to the direction of propagation is to use an associated prism to change the direction, as shown in FIG. 6. The DMD is illuminated with light normal to its surface as before, and a prism is placed in the reflected beam. The directions and the angles of the prism have been adjusted to remove the angular offset of the DMD. The lens is then used in a normal fashion.

The effect of the prism can be demonstrated analytically. To do this, a ray matrix description is utilized. A ray with slope p[o]incident on a DMD mirror/pixel leaves the pixel with slope p[1]. The 3 x 3 ray matrix for the DMD whose mirror elements are tipped by +/- [theta] is given by [theta] <=26> Get Mathematical Equation

The first of the three linear equations represented by the matrix equation shows that upon reflection the position of the ray remains constant and the second linear equation shows that the slope changes direction by +/- 2 [theta] . Similarly, it has been shown that for the prism the ray matrix for a prism of small angle [alpha] and index n[1]is given by [alpha] <=27> Get Mathematical Equation

Return to the situation in FIG. 6 where a DMD is on the left so that the light is reflected upward, translates a distance d and passes through the prism. The effect of the angle on the DMD can be cancelled. To find the conditions, multiply the matrices for the DMD, the translation and the prism and accept that the product be equivalent to that for the translation by itself. Thus, [alpha] [theta] [theta] [theta] [alpha] <=28> Get Mathematical Equation

It is seen by taking the product that the angular offset of the DMD is cancelled if [alpha] = 2 [theta] /(n - 1). The horizontal axis is then translated upward in the y direction by a distance y[d] = + 2d [theta] . The axis is selected by choosing for the position and input slope y[o] = 0 and p[o] = 0. Using these in the previous equations, we find the output position is y[1] = + 2d [theta] . This is reasonable because the axis has been raised by a distance y[d] = 2d [theta] in translating a distance d. To compensate for this, set y[1] = y[2] - y[d] = y[2] - 2 [theta] d. This affects only the top line in the above equation. The result is the following matrix equation. Note that the equation has the form of a simple translation by a distance d. <=29> Get Mathematical Equation

Thus, with the redefined axis the prism compensates nicely for the angular deflection of the DMD.

The equivalent of the Dual White Cell with unequal arms using the DMD is shown in FIG. 7. There the DMD 31 is at the left and to the right of the DMD are lens f136 and spherical Mirror C 35. There are two paths, depending whether a given pixel reflects light up or down. For light reflected downwards there are prism P[1]37, lens f238 and Spherical Mirror B 39. For light reflected upward, there are Prism P[2]32, lens f'[2]33 and Mirror M 34. The prisms counteract the angular effects of the DMD as described. Of the two sets of conditions, the SLM-imaging conditions, and the light-conserving conditions, it is simpler to consider the light-conserving conditions first. The light-conserving conditions are that Spherical Mirrors B, C, and M be imaged onto each other and no light is lost going around the outsides of Mirrors B, C or M. This is accomplished by placing Mirrors B, C, and M in the focal planes of Lenses f[2], f[1], and f'[2]respectively. The curvatures of Mirrors B, C, and M are all chosen so that in conjunction with lenses f[2], f[1], and f'[2]the DMD is imaged back onto itself. As has been shown, images of the centers of curvature of Mirrors B, C and M through Lenses f[1], f[2], and f'[2]lie on the DMD. The result is the equivalent of the dual cell in FIG. 3 with equal arms. The light can go from Mirror C to Mirror B and back or from Mirror C to Mirror M and back depending on the state of a given pixel. The DMD decides between the two paths on any particular bounce.

For the DMD imaging conditions, Lens f[3]can be chosen to image the DMD onto Lens f[4]and the radius of curvature of Spherical Mirror D chosen so that its center of curvature is on Lens f[4]. As a result, light coming from the DMD is imaged by Lens f[3]onto Lens f[4], then re-imaged by Spherical Mirror D back onto Lens f[4]and imaged by Lens f[3]back onto itself as required. Equivalently, since the center of curvature of Spherical Mirror lies on Lens f[4], it is imaged by Lens f[3]onto the DMD as required.

In operation, light comes in from an input source below the unit. Light from the outside source is imaged onto a pixel in the "down" position which acts as a turning mirror. That pixel directs the light to Spherical Mirror 34 which then images it onto a pixel in the "up" position. The pixel then directs the light to Spherical Mirror 35 which images it back to the DMD. The light is now considered to be "in the unit". The choices of tip of the DMD to direct to light to the short path of Spherical Mirror 34 and back to Spherical Mirror 35 or to the long path of Spherical Mirror 39 and back to Mirror 35, as can be appreciated from the array shown in FIG. 7. After the last bounce off Spherical Mirror 35, the light goes to Spherical Mirror 39 and to a pixel on the DMD which is in the "up" position and directs the light out of the cell.

The distance from the DMD to the lenses f[1], f[2], and f'[2]is designated d[o], and the focal lengths of Lenses f[1], f[2], and f'[2]can be taken to be equal. Starting from the turning mirror pixel, light travels a distance 4(d[o] + f[1]) to Spherical Mirror B and back and then to Spherical Mirror C and back to get "into the system". The light can go either to Mirror B and back and to Mirror C and back, a distance of 4(d[o] + f[1]) or it can go to Mirror D and back and then to Mirror C and back, a distance of 4(d[o] + f[1]) + 8f[4]. To exit the system, the light goes to Mirror D and to the turning pixel, a distance of 2(d[o] + f[1]) + 8f[4]. Then if there are m bounces, m[2]of which are switched to Mirror D, the expression for the transit time through the cell is

T = (1/c)[4(d[o] + f[1]) + ((m - m[2])4(d[o] + f[1]) + m[2]4(d[o] + f[1] + 2f[4])) + 2(d[o] + f[1] + 2f[4])] = T[o] + m[2] [DELTA] T

where the constant part, T[o],and the adjustable part, [DELTA] T are given by

T[o] = (1/c)(6(d[o] + f[1]) + 8f[4] + m4(d[o] + f[1]))

[DELTA] T = (1/c)8m[2]f[4]

The time increment is (1/c)8m[2]f[4]and there are m[2]choices, as before.

The binary cell of FIG. 5 is considered next, with auxiliary mirrors and a means for extending distances. The equivalent of FIG. 5 with the auxiliary mirrors is shown in FIG. 8. FIG. 8 is derived from the equal arm cell made with the DMD. The difference is that Spherical Mirrors B and M have been realigned so that the DMD is imaged onto the auxiliary mirrors rather than back onto itself. The transition to DMD-based optics has been made. All that remains is to add the either the glass blocks or the optical waveguide. The area of Auxiliary Mirror II can then be divided into strips. Auxiliary Mirror II can now be removed and replaced with the glass blocks or the lens waveguide. In FIG. 11, Auxiliary Mirror II has been removed and replaced with the entrance to the lens waveguide. The operation is the same as described in the dual arm binary device.

The preferred embodiments herein disclosed are not intended to be exhaustive or to unnecessarily limit the scope of the invention. The preferred embodiments were chosen and described in order to explain the principles of the present invention so that others skilled in the art may practice the invention. Having shown and described preferred embodiments of the present invention, it will be within the ability of one of ordinary skill in the art to make alterations or modifications to the present invention, such as through the substitution of equivalent materials or structural arrangements, or through the use of equivalent process steps, so as to be able to practice the present invention without departing from its spirit as reflected in the appended claims, the text and teaching of which are hereby incorporated by reference herein. It is the intention, therefore, to limit the invention only as indicated by the scope of the claims and equivalents thereof.

CLAIMS:
What is claimed is:

[*1] 1. An apparatus for optically generating time delays in signals comprising:(a) an input light source, said input light source adapted to generate at least one individual light beam from at least one direction; (b) an input mirror adapted to reflect said at least one individual light beam; (c) a plurality of optical elements configured so as to define a plurality of possible light paths for each said light beam reflected by said input mirror; (d) at least one refocusing optical element adapted to restrict the divergence of a light beam diverted by said optical elements through at least one of said light paths; (e) a spatial light modulator adapted to select a path from among said light paths for each pass of a said light beam through said optical elements; (f) an output mirror adapted to reflect each said light beam emerging from said optical elements; and (g) at least one receiving device adapted to receive a said light beam reflected by said output mirror and determine the delay in the light beam; wherein at least said spatial light modulator is encountered at least twice by each said light beam from free-space before emerging from said

optical elements to said output mirror.

[*2] 2. An apparatus according to claim 1 wherein at least one of said plurality of optical elements is encountered by a said light beam so as to form an array of intersection light points.

[*3] 3. An apparatus according to claim 1 wherein said input mirror is adjustable.

[*4] 4. An apparatus according to claim 1 wherein said plurality of optical elements is selected from the group consisting of mirrors, lenses, gratings, and prisms.

[*5] 5. An apparatus according to claim 1 wherein said output mirror is adjustable.

[*6] 6. An apparatus according to claim 1 additionally comprising at least one system of waveguides, said waveguides adapted such that the lengths of a plurality of said light paths may be varied in a fixed space comprising a subset of said optical elements.

[*7] 7. An apparatus according to claim 1 wherein said spatial light modulator consists of a polarizing spatial light modulator adapted to change the polarization of a said light beam directed to said spatial light modulator.

[*8] 8. An apparatus according to claim 7 additionally comprising a beam splitting device adapted to direct a said light beams along a said light path depending on the polarization of the light beam.

[*9] 9. An apparatus according to claim 1 wherein said spatial light modulator consists of a deformable mirror device spatial light modulator adapted to reflect a said light beam to at least one of said plurality of light paths.

[*10] 10. A method for optically generating time delays in signals, said method comprising the steps of:a) modulating an input signal onto an optical beam; b) passing said optical beam through an apparatus for optically generating time delays, said apparatus comprising: (i) an input mirror adapted to reflect said optical beam; (ii) a plurality of optical elements configured so as to define a plurality of possible light paths for said optical beam reflected by said input mirror; (iii) at least one refocusing optical element adapted to restrict the divergence of said optical beam diverted by said optical elements through at least one of said light paths; (iv) a spatial light modulator adapted to select a path from among said light paths for each pass of said optical beam through said optical elements, wherein at least said spatial light modulator is encountered at least twice by each said light beam from free-space before emerging from said optical elements to an output mirror; and (v) an output mirror adapted to reflect said optical beam emerging from said set of optical elements; and c) down-converting said optical beam to an output signal.

[*11] 11. A method according to claim 10 additionally comprising the step of adjusting said input mirror to appropriately direct said optical beam into said set of optical elements.

[*12] 12. A method according to claim 10 additionally comprising the step of adjusting said output mirror to appropriately direct said optical beam

emerging from said set of optical elements.

[*13] 13. A method according to claim 10 additionally comprising the step of receiving said optical beam reflected by said output mirror and determining said delay.

[*14] 14. A method according to claim 10 wherein said apparatus additionally comprises at least one system of waveguides, said waveguides adapted such that the lengths of a plurality of said light paths may be varied in a fixed space comprising a subset of said optical elements.

[*15] 15. An apparatus according to claim 10 wherein said spatial light modulator consists of a polarizing spatial light modulator adapted to change the polarization of a said optical beam directed to said spatial light modulator.

[*16] 16. An apparatus according to claim 15 additionally comprising a beam splitting device adapted to direct a said optical beam along a said light path depending on the polarization of the optical beam.

[*17] 17. An apparatus according to claim 10 wherein said spatial light modulator consists of a deformable mirror device spatial light modulator adapted to reflect a said optical beam to at least one of said plurality of light paths.

[*18] 18. An apparatus according to claim 1 additionally comprising at least a second input light source, said at least a second input light source adapted to generate at least one individual light beam from at least one direction.

[*19] 19. An apparatus according to claim 18 wherein said input light source and said at least a second input light source create an array of intersection light points on at least one optical element.

[*20] 20. An apparatus according to claim 1 wherein each said light beam reflected by said input mirror produces an array of intersection light points using no fewer than two of said optical elements.

[*21] 21. An apparatus for optically generating time delays in signals comprising:an input device for receiving at least one individual light beam from a light beam source, said input device capable of reflecting said at least one individual light beam; a plurality of optical elements configured to define a plurality of possible light paths for each said light beam reflected by said input device wherein each said light path of said plurality defines a distance, wherein one of said light paths of said plurality defines a path of shortest distance, said plurality of optical elements comprising: (i) at least one refocusing optical element adapted to restrict divergence of a light beam diverted by an optical element of said plurality of optical elements; and (ii) a spatial light modulator adapted to select a path from among said plurality of possible light paths for each said light beam encountering said spatial light modulator, wherein said spatial light modulator reflects each said beam of light through at least one path thereby generating a time delay prior to reflecting each said beam of light returning to said spatial light modulator from at least one of said plurality of optical elements in said path to an output device; and an output device for receiving each said beam of light from said spatial light modulator and for reflecting each said beam of light to a receiving device.

[*22] 22. An apparatus according to claim 21 wherein said time delay is generated by reflecting said beam of light on a path of greater distance relative to said path of shortest distance.

[*23] 23. An apparatus according to claim 21 wherein said input device is a mirror.

[*24] 24. An apparatus according to claim 21 wherein said output device is a mirror.

[*25] 25. An apparatus according to claim 21 wherein at least one optical element of said plurality of optical elements is selected from the group consisting of mirrors, lenses, gratings, beam splitters and wave guides.

[*26] 26. An apparatus according to claim 21 wherein said spatial light modulator is selected from the group consisting of polarizing spatial light modulators and deformable mirror spatial light modulators.

[*27] 27. A method for optically generating time delays in signals, said method comprising the steps of:modulating an input signal onto an optical beam; passing said optical beam through an apparatus for optically generating time delays, said apparatus comprising: an input device for receiving at least one individual light beam from a light beam source, said input device capable of reflecting said at least one individual light beam; a plurality of optical elements configured to define a plurality of possible light paths for each said light beam reflected by said input device wherein each said light path of said plurality defines a distance, wherein one of said light paths of said plurality defines a path of shortest distance, said plurality of optical elements comprising: at least one refocusing optical element adapted to restrict divergence of a light beam diverted by an optical element of said plurality of optical elements; and a spatial light modulator adapted to select a path from among said plurality of possible light paths for each said light beam encountering said spatial light modulator, wherein said spatial light modulator reflects each said beam of light through at least one path thereby generating a time delay prior to reflecting each said beam of light returning to said spatial light modulator from at least one of said plurality of optical elements in said path to an output device; and an output device for receiving each said beam of light from said spatial light modulator and for reflecting each said beam of light to a receiving device; and down-converting said optical beam to an output signal.

Pat. No. 4225938 printed in FULL format.

4,225,938

<=2> GET 1st DRAWING SHEET OF 4

Sep. 30, 1980

Time-integrating acousto-optical processors

INVENTOR: Turpin, Terry M., Columbia, Maryland

ASSIGNEE-AT-ISSUE: The United States of America as represented by the Director of the National Security Agency, Washington, District of Columbia (06)

APPL-NO: 966,849

FILED: Dec. 5, 1978

INT-CL: G06G 9#00; G06G 7#19

US-CL: 708#816; 359#285; 359#561; 708#831;

CL: 708;359;

SEARCH-FLD: 364#819, 822, 713, 837; 350#162SF, 358; 346#108

REF-CITED:

U.S. PATENT DOCUMENTS

3,509,453	4/1970	Wilmotte	364#822
3,512,871	5/1970	Zweig	350#162SF
3,545,841	12/1970	Dentino et al.	350#358
3,634,749	1/1972	Montgomery	364#822
3,641,355	2/1972	Preston, Jr.	364#822
3,648,039	3/1972	Kowalski	364#822
3,661,441	5/1972	Uchida et al.	350#358
3,746,427	7/1973	Foster	350#358
3,872,293	3/1975	Green	364#822
3,958,863	5/1976	Isaacs et al.	350#358
4,107,701	8/1978	Sprague et al.	346#108
4,110,016	8/1978	Berg et al.	350#358
4,123,142	10/1978	Fleming et al.	364#822
4,158,503	6/1979	Balasubramanian	350#162SF

OTHER PUBLICATIONS

Sprague et al., Time Integrating Acoustic Correlator Applied Optics, Jan. 1976, vol. 15, No. 1, pp. 89-92.

PRIM-EXMR: Gruber, Felix D.

LEGAL-REP: Utermohle; John R.
Young; Barry N.
Maser; Thomas O.

CORE TERMS: processor, modulator, beam, optical, detector, processing,

two-dimensional, frequency, spatial, dimension, mirror, cell, time-integrating, equation, acousto-optic, oscillator, correlator, one-dimensional, input, distributed, architecture, modulating, ambiguity, amplitude, intensity, phase, correlation, integration, bandwidth, moving

ABST:
Disclosed are acousto-optical information processors employing a two-dimensional, time-integrating architecture. These three-product type processors are multi-purpose processors which can perform a variety of complex signal processing operations in two-dimensions, without requiring two-dimensional spatial light modulators. Typical of these processing operations are two-dimensional correlation, spectrum analysis, and cross ambiquity function processing. Some of the two-dimensional processing operations are made possible by the incorporation into a two-dimensional correlator of a distributed local oscillator, which may be implemented with mechanical-optical or electro-optical techniques. The acousto-optical processors may be easily implemented with readily available optical and acousto-optical components.

NO-OF-CLAIMS: 16

EXMPL-CLAIM: <=17> 1

NO-OF-FIGURES: 7

NO-DRWNG-PP: 4

SUM:

BACKGROUND AND SUMMARY OF THE INVENTION

The present invention relates generally to the field of optical processors, and more particularly to the field of time-integrating optical processors for performing real-time correlations, transforms, and other processing operations.

There are a number of applications where it is desirable to process in real-time, information bearing signals. This is particularly true in the communications and radar processing fields. Normally, in these and similar fields, it is desirable to process in real-time, signals having fairly large information bandwidths. General purpose digital computers are capable of performing some of these processing operations. However, because of their limited speed, they are incapable of performing all but the very simplest of such processing operations in real-time. Special purpose digital signal processors, configured as array processors, typically can perform real-time processing operations if the information bandwidth of the signals is not too large. However, array processors are expensive, sophisticated, hardware devices which are difficult to program, and often the cost of such digital processing at very high data rates is prohibitive.

Because of their large time-bandwidth products and relative simplicity, optical processors represent an attractive alternative to processing large data rate signals. In the past, most optical processors have been of the space-integrating type. The basic principle involved in space-integrating processors is to place one signal into a light modulator so that the time

window of the signal containing many cycles is simultaneously present in the optical system. This signal is then made to modulate a light beam to provide an optical signal which contains spatial variations related to the information signal. The resulting optical signal is then imaged with a lens system onto a second signal, which may be displayed in the form of transmission variations in an optical mask (transparency) to provide spatial filtering operations, or the second signal may be introduced as phase variations in the optical signal in a second light modulator. The light modulated by the two signals is then imaged with a second lens onto a single detector whose time-varying output represents the processed input signal. This second lens system integrates the total light signal in spatial dimensions, to provide a signal having intensity variations which is focused onto the single detector. Space-integrating optical processors suffer from the disadvantage that they are limited in time-bandwidth product to the time-bandwidth product of the optical components used in the processor.

Another type of optical processor employs a time-integrating architecture. Time-integrating optical processors basically differ from space-integrating processors in that instead of spatially integrating light onto a single detector, time-integrating devices perform a time integration of the light signal at each point in space. Accordingly, they overcome the limitation of the time-bandwidth product imposed by the optical components employed. Furthermore, they offer a greater flexibility than the space-integrating type of processor, and have less stringent construction tolerances.

A time-integrating correlator is the simplest processing operation to implement using the time-integrating architecture, and is the basic architecture from which other processing operations can be configured. Typical of devices of this type are the time-integrating correlators disclosed in U.S. Pat. No. 3,634,749 to Montgomery, and in Robert A. Sprague and Chris L. Koliopoulos, "Time Integrating Acousto-Optic Correlator," Applied Optics, Vol. 15, No. 1, January 1976. Both references disclose the use of acousto-optic devices as one-dimensional light modulators to provide one-dimensional time-integrating correlators. While these one-dimensional optical processors are useful for performing simple processing operations, there are many applications that require more sophisticated processing which is incapable of being performed using a one-dimensional processor architecture. For example, in the radar processing field, a radar signal is returned from a target shifted both in time and in frequency due to doppler phenomena. This requires ambiguity function processing, to be described more fully hereinafter, which can not be performed by a simple one-dimensional architecture. Such processing requires a two-dimensional architecture. Similarly, there are other processing operations which require a two-dimensional optical processing architecture.

Two-dimensional optical processors may be implemented by utilizing two-dimensional spatial light modulators, such as coherent light valves. Light valves, however, are relatively bulky and expensive devices to use in optical processing systems. Recent advances in optical processing technology, have resulted in significant improvements in acousto-optic devices, such as Bragg cells. These devices are small, compact, and relatively inexpensive. Furthermore, they provide relatively large bandwidths.

Accordingly, it is an object of the invention to provide new and improved two-dimensional optical processors which do not require two-dimensional spatial light modulators.

It is also an object of the invention to provide a time-integrating optical processor architecture.

It is a further object of the invention to provide optical processors capable of performing complex processing operations, such as three-product type processing.

It is a still further object of the invention to provide optical processors employing distributed local oscillators to perform certain processing operations.

It is additionally an object of the invention to provide optical processors employing electronic techniques to provide flexibility and dynamic processing capabilities.

It is also an object of the invention to provide optical processors capable of performing in real-time, processing operations on very high data rate signals.

A time-integrating optical processor having these and other advantages might include, a beam of light, means for modulating the light in first and second mutually orthogonal spatial dimensions using one-dimension spatial light modulators, and a two-dimensional time-integrating detector for detecting the modulated light beam and for providing an output signal representative of the processed information.

DRWDESC:
BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a generalized illustration of a one-dimensional time-integrating correlator.

FIG. 2 is a generalized illustration of a two-dimensional time-integrating ambiguity processor, employing a moving mirror distributed local oscillator.

FIG. 3 is a model of the two-dimensional ambiguity function processor of FIG. 2, useful in explaining the operation of the processor.

FIG. 4 is a detailed embodiment of the processor of FIG. 2.

FIG. 5 is a generalized illustration of a two-dimensional time-integrating three-product type processor.

FIG. 6 is a generalized illustration of an alternative embodiment of a two-dimensional time-integrating three-product processor.

FIG. 7 is an illustration of a two-dimensional spectrum analyzer output.

DETDESC:

Description of Preferred Embodiments

FIG. 1 is an illustration of a one-dimensional time integrating correlator, drawn to illustrate the principles involved and not all of the optics required to implement it. A source of light 10 produces a light beam which is intensity

modulated in an acousto-optical point modulator 11, which may be a Bragg cell, by a signal f(t). The diffracted light from Bragg cell 11 is then expanded in a horizontal dimension, by optics not illustrated, to illuminate a second acousto-optic modulator 12, which may also be a Bragg cell, fed by a second signal g(t). The light beam is intensity modulated in modulator 12 by g(t - x/v), where x is the horizontal position along the Bragg cell and v is the velocity of sound in the cell. The doubly diffracted light from Bragg cell 12, expanded in the horizontal dimension, is imaged onto a linear detector array of photodiodes or CCD's, 15, which integrates the light intensity. The output of the detector at position x of the array is given by [See equation in original](1)

which is the one-dimensional cross-correlation function of f(t) and g(t), where T is the detector integration time. With currently available detectors, the integration time can typically range from 100 microseconds to several seconds.

The correlator of FIG. 1 may be implemented either as a coherent or non-coherent optical system. Although non-coherent systems are somewhat simpler in terms of implementation, they have certain limitations not possessed by coherent systems. A disadvantage of non-coherent systems is that the input data and the input response of the optical system must be non-negative intensity distributions. There is no simple way in a non-coherent system to process bipolar inputs with bipolar inpulse responses. In the non-coherent correlator, the input signals f(t) and g(t) are placed as amplitude modulation on a carrier frequency centered in the passband of the Bragg cell, hence, the Bragg cell bandwidth must be twice the signal bandwidth, and the Bragg cells are operated in an intensity (square of light amplitude) modulation mode. In this mode, the intensity, rather than amplitude, of the modulated light is proportional to the driving voltage.

Bragg cells are currently available with bandwidths from 10 MHz to 1 GHz with corresponding delay times of 100 microseconds to 1 microsecond, respectively. If a 200 MHz bandwidth Bragg cell having a 10 microsecond delay time is used, and the detector integration time is 1 millisecond, then two 100 MHz signals can be correlated over a range of offsets from 0 to 10 microseconds, with a processing gain (integration time X bandwidth) of 10<5>. If 1000 detector elements are used in the linear detector, the array will produce an output rate of 10<6 >samples per second. This is a convenient rate for digital post-processing, which could be utilized to extend the integration time, and improve processing gain. This illustrates the processing gain and data rate reduction that are characteristic of the time-integrating architecture. The output of the correlator, equation (1), is the cross correlation of the two input signals f(t) and g(t).

If light source 10 is a laser, the correlator of FIG. 1 is a coherent time-integrating correlator. Here, the passband of interest in the input signals is upconverted to the passband of the Bragg cell with a single sideband modulator, on a carrier placed at one extreme of the passband of the Bragg cell. The light modulation is linear in amplitude rather than intensity, as is the case with the non-coherent system. Further, since the input to the Bragg cells is single sideband rather than double sideband amplitude modulation, the bandwidth of the system is increased by a factor of two. In addition, the drive requirements on the cells are reduced because Bragg cells are linear in

amplitude at low diffraction efficiencies.

The coherent correlator requires a coherent reference beam at the detector, which is summed with the processing beam to detect points of correlation. The summing operation compares the phases of the reference and processing beams. Where the beams are in phase, the magnitudes add algebraically; where out of phase, they subtract. At a point where two signals are correlated, their relative phase difference remains constant, producing a constant magnitude which builds up for the integration time of the detector. When uncorrelated, their relative phase difference changes as a function of time and the amplitude integrates to some small (nominally zero) average value. Points of correlation then appear as deviations from this average. By proper selection of the reference beam, the output may be placed on a spatial carrier to extract the real and imaginary correlation components, simultaneously, thereby providing a true complex correlation processing operation.

There exists a certain class of processing operations which can not be performed by the one-dimensional processor of FIG. 1. Processing operations of the so called three-product type, exemplified by the generalized equation (15), infra, and explained in more detail hereinafter, can only be performed in a two-dimensional optical processor. As used herein, "two-dimensional" optical processors refers to processors of the three-product type which process signals in two or more dimensions. An optical processor is not a "two-dimensional" processor merely because it happens to use a two-dimensional detector. An example of two-dimensional processing operations includes ambiguity function (time-frequency correlation) processing, which is needed to correlate signals at unknown carrier frequencies. The problem arises in radar processing when a coded radar pulse is returned doppler shifted by a moving target. According to one aspect of the invention, a two-dimensional time-integrating processor capable of performing cross ambiguity function processing is illustrated in FIG. 2.

The cross ambiguity function is defined as [See equation in original](2)

where omega = 2 pi f and tau is a time delay. If f(t) and g(t) are doppler shifted replicas of each other, as would be the case where f(t) is a reference of the pulse transmitted by the radar and g(t) is the returned pulse, the term e<j omega t >cancels the doppler shift at the correct frequency, omega , resulting in the correlation function of the unshifted signals. At frequencies not equal to the doppler frequency, the integral of equation (2) is zero and no output is obtained. The doppler shift imposed on the return radar signal, and hence its frequency, is seldom known, although the range of expected doppler can typically be estimated. Therefore, the return signal must be multiplied by a plurality of frequencies within the expected range in order to determine which frequency zero beats with the returned signal to provide a correlator output. This essentially requires a distributed local oscillator that oscillates at all frequencies within the expected range and which may simultaneously be applied to the return signal by the processor.

FIG. 2 is a generalized illustration of a coherent, two-dimensional, time-integrating optical processor. FIG. 2 is drawn to illustrate the concepts involved, not the optics. A laser, 20, provides a beam of coherent light, which is split into two beams, a processing beam and a reference beam, by beam splitter 21. The processing part of the beam from beam splitter 21 is provided

to a one-dimensional spatial light modulator comprising acousto-optic Bragg cell light modulators 11, 12. Modulator 11 operates as a point modulator to modulate the processing beam with a signal f(t). The beam is expanded, by optics not illustrated, in the horizontal, x, dimension and applied to the second acousto-optic Bragg cell modulator 12, which modulates the beam with the second signal, g(t). The output from modulator 12 is then expanded in a vertical, y, direction by a lens system not illustrated, and imaged onto a two-dimensional integrating detector array 22. The light amplitude imaged on the detector has a variation of f(t) g(t - x/v) in the x, or horizontal dimension and is uniform in the vertical or y dimension. Light source 20 and light modulators 11 and 12 form a one-dimensional time-integrating correlator similar to that illustrated in FIG. 1. The light from modulator 12 however has been expanded in a vertical direction and imaged on a two-dimensional detector as opposed to the linear detector array of FIG. 1.

The reference portion of the coherent beam from laser 20 which is split off by beam splitter 21 is reflected by a mirror 25 and imaged onto the two-dimensional detector 22, where it is combined with the light from light modulator 12. If the mirror is stationary, it provides a plane wave Ae< alpha x>. The light amplitude on the detector is given by f(t) g(t - x/v) + Ae < alpha x >and the corresponding intensity is f(t) g(t - x/v)<2> + A<2> + 2A f(t) g(t - x/v) cos alpha x. If alpha , the spatial carrier of the reference plane wave, is selected to be equal to or greater than the spatial bandwidth of the correlation function, the correlation term can be extracted with a high pass filter on the output of the detector. This is a coherent, one-dimensional, time-integrating correlator. However, if the signal g(t) is time-varying or a doppler shifted replica of f(t), the correlation output will be zero.

If the mirror 25 is permitted to rotate with a uniform angular velocity about a horizontal axis through its center, and the reflected light beam is imaged onto the detector plane 22, then for small linear motions of the mirror such that the tan x = x approximation is maintained, the light from the mirror will be linearly phase shifted in time (doppler shifted) by e<j4 pi theta yt/ lambda >, where theta is the angular velocity of the mirror, lambda is the wavelength, and y is the distance from the axis of the mirror. The moving mirror constitutes a one-dimensional spatial light modulator which modulates the reference beam in the vertical dimension.

The light amplitude on detector 22 is now [See equation in original](3)

and the corresponding intensity is [See equation in original](4)[See Original Patent for Chemical Structure Diagram]

If the detector is allowed to integrate for a period of T, and only the term on the carrier is considered, then the output is [See equation in original](5)

This is a true complex cross ambiguity function on a spatial carrier alpha . The processor is two-dimensional with the x axis of the display representing the relative time delay between f and g, and the y axis corresponding to the

doppler frequency difference.

As an illustration let f(t) = g(t)e<j> DELTA omega <t>, where DELTA omega is the doppler frequency shift. The light intensity is [See equation in original](6)[See Original Patent for Chemical Structure Diagram]

and the output from the detector is [See equation in original](7)

The cosine term is stationary in time only if (4 pi / lambda) theta y = DELTA omega . If DELTA omega and (4 pi / lambda) theta y differ by one cycle over the period T, the cosine integrates to zero. At (4 pi / lambda) theta y = DELTA omega the output is the autocorrelation of g(t). The moving mirror produces a distributed local oscillator that oscillates at all possible frequencies over a given range as a function of y, and zero beats out any carrier difference in that range to produce an output from the detector. Carrier phase differences appear as a phase shift on the spatial carrier alpha . The frequency resolution is the reciprocal of the detector integration time. Each scan of the detector 22 by the light beam reflected from mirror 25 represents a frame. After each frame, the mirror is reset to its original position to repeat its scan.

A more complete understanding of the apparatus of FIG. 2 can be had by reference to FIG. 3, which illustrates an ambiguity processing model. As previously described, g(t), which may be a time delayed, doppler shifted replica of a transmitted radar signal, is input to a Bragg cell 12 which functions as a delay line. As g(t) propagates through the Bragg cell, it is delayed in time by an amount x/v, such that if taps 26-26 are placed at various points along the delay line, the output signal at each tap will be g(t - x/v). The output signal on taps 26-26, is then multiplied by the signal f(t) in a plurality of multipliers 27-27 to produce an output signal which is the product of f(t) and g(t) delayed by various times. To each of the output signals from multipliers 27-27, there is added in adders 30-30 a plurality of reference waves generated by local oscillators 31-31. The composite signals are then imaged onto the two-dimensional detector 22. The detector receives f(t)g(t - x/v) plus a local oscillator and forms the product through the square law process. Detector 22 can be considered as a plurality of photocells 32-32 arranged in a two-dimensional array. Each detector cell 32-32 integrates the resulting composite light intensity incident upon it for a given period of time, T. The outputs of the detector cells 32-32 are then provided as a detector output.

Assume for purposes of illustration, that g(t) is a return radar wave with a zero doppler shift, and that local oscillators 31-31 provide a reference plane wave of constant frequency. At the particular delay line tap 26 where the delay x/v is equal to the round-trip delay time of the radar signal, f(t) and g(t) will add in phase to produce a detector output. Each detector cell in the vertical column corresponding to the tap where the relative time delays are equal will provide an output, such that if detector 22 is a two-dimensional display, a vertical line will appear at a horizontal position which corresponds to the time delay x/v. Although the display is two-dimensional, the processor is only a one-dimensional correlator. If, however, g(t) is doppler shifted, the phases of g(t) and f(t) will not coincide and no output will be obtained. If

local oscillators 31-31 are allowed to supply a plurality of different frequencies, at the point in the vertical dimension where the frequency of the local oscillator matches the doppler frequency on g(t), a zero beat will be obtained.

If the number of taps 26-26 on delay line 12 is allowed to approach infinity, a continuous delay between zero and x[max]/v can be obtained. This is the case with the Bragg cell modulator since the light is continuously delayed along the length of the cell. Similarly, if the number of local oscillators is allowed to approach infinity, a continuously distributed local oscillator is obtained. The moving mirror produces a light beam having continuously increasing frequency shift with distance from the axis of relative rotation of the mirror. This light beam is imaged on the detector and thus constitutes a continuously distributed local oscillator in the vertical dimension.

FIG. 4 is a detailed embodiment of the optical processor of FIG. 2. Coherent light from laser 20 is first passed through a vertical polarizer 35 and split by beam splitter 21 into two optical beams. The processing beam is fed to a shear wave Bragg cell 36 which functions as a point modulator to modulate the amplitude of the coherent beam with the signal f(t). The light diffracted by Bragg cell 36 is rotated 90 degrees in polarization, and is passed through a horizontal polarizer 37 which blocks the undiffracted light. Cylindrical lens 40 spreads the light in a horizontal dimension where it is collimated by a second cylindrical lens 41 and passed to a stationary 45-degree mirror 42. The light reflected from mirror 42 is modulated in a second Bragg cell 45 by g(t). The diffracted light from Bragg cell 45 is expanded in a vertical dimension by cylindrical lens 46, and collimated and imaged by cylindrical lenses 47, 48 through a vertical polarizer 50 onto cylindrical lens 51. The light from cylindrical lens 51 is passed through a beam combiner 52 and imaged onto the two-dimensional detector array 22, which may be a vidicon, for example.

The second beam of light, 55, from beam splitter 21 is focused by lens 56 and 57 onto beam splitter 60. Light is reflected by beam splitter 60 onto the scanning mirror 25, which rotates about a horizontal axis 61. The light is reflected by scanning mirror 25 through beam combiner 60 where it is imaged by lenses 62 and 65 onto beam combiner 52. Beam combiner 52 reflects this light onto detector 22 where it is combined with the light beam modulated by f(t) and g(t). Detector 22 integrates the light intensity impinging on it and provides an output which, as previously described, represents the ambiguity function. This output may be further processed, if desired, to provide longer integration time and, consequently, improved resolution.

It should be noted that the optical processor requires only imaging and not transforming lenses. Hence, optical tolerances may be less rigid, since uniformity of response is not required, and the light source need be spatially coherent over only one resolution spot.

The optical components illustrated in FIG. 4 are all standard, readily available optical components. Scanning mirror 25 may be implemented in a number of available ways. For example, it may be implemented similar to the mirror in a galvanometer, where the rotation is controlled by the electromagnetic field produced by a circuit flowing in a coil. The scanning of scanning mirror 25 is adjusted to produce the desired frequency shift across the detector. As previously mentioned, the rotation of the mirror is controlled such that the the tan x = x approximation is maintained. Each scan of the mirror represents a

complete frame of information.

Distributed local oscillators can be produced by moving mirrors or any component that produces a dynamically tilted wave front. For example, the transform of a moving point source is a distributed local oscillator. Hence, distributed local oscillators may be implemented electronically to avoid the necessity for moving parts, such as the scanning mirror utilized by the apparatus of FIGS. 2 and 4. FIG. 5 illustrates an alternative processor to the processor illustrated in FIG. 2, that does not use a moving mirror to produce the distributed local oscillator. As will become apparent in the description, the processor of FIG. 5 has certain advantages over the processor of FIG. 2, including the fact that it has greater flexibility to perform a larger variety of operations, without the necessity for changing the optics.

Referring to FIG. 5, the moving mirror, 25, of FIG. 2 is replaced by a stationary mirror 70, and acousto-optical Bragg cell modulators 71 and 72 are added. The light reflected by mirror 70 is modulated in light modulators 71 and 72 by f[y](t) and g[y](t), the purpose of which will be explained more fully hereinafter.

Considering first the correlator portion of the optical processor of FIG. 2; assume that the moving mirror 25 is stationary. Assume further, that f(t) and g(t) are both chirps, i.e., signals having a frequency which is linearly increasing with time. That is, [See equation in original](8)

where omega 0 and a are, respectively, the carrier frequency and angular acceleration of the chirp signal. The positive order diffraction from one light modulator is [See equation in original](9)

and the negative order diffraction from the second light modulator is [See equation in original](10)

Hence, the doubly diffracted light is [See equation in original](11)[See Original Patent for Chemical Structure Diagram]

This is a distributed local oscillator with a phase distortion in space. This phase distortion is unimportant if only relative phase measurements are required, and in any case it can be removed after detection as a fixed pattern. Thus, a distributed local oscillator has been produced as an electronic modulation on a light beam. This leads to the processor in FIG. 5.

Referring to FIG. 5, the light amplitude in the output plane at detector 22 is [See equation in original](12)

After integration and high pass filtering, it can be shown that the detector output is [See equation in original](13)

which is a two-dimensional correlation function on a spatial carrier alpha . Thus, the processor of FIG. 5 is a two-dimensional time-integrating correlator, and a large class of operations are possible using this basic processor architecture. Note that since the signals f[x](t) and f[y](t) are introduced into point modulators, i.e., Bragg cells 11 and 71, they may be combined into a single function and light modulator h(t) = f[x](t) f[y](t), as illustrated in FIG. 6. If f[y](t) and g[y](t) are chirps, i.e., [See equation in original](14)

the two-dimensional correlator of FIG. 5 becomes a cross ambiguity function processor.

The processor of FIG. 6 is an alternative embodiment of the processor of FIG. 5. By combining f[x](t) and f[y](t) in an electronic modulator 75 (substituting an electronic multiplication for an optical multiplication), and using the resulting function h(t) as a single input to Bragg cell 11, Bragg cell 71 can be eliminated. Furthermore, the processor can be physically configured as illustrated in FIG. 6 such that Bragg cell 72 is used to directly modulate the light from Bragg cell 12. Thus, the processors illustrated in FIGS. 5 and 6 are so-called three-product processors, which can be used to provide processing operations of the form [See equation in original](15)

By proper selection of the functions h(t), g[x](t) and g[y](t), a large variety of processing operations can be performed. Furthermore, since h(t), g[x](t) and g[y](t) may be generated electronically, and optical multipliers interchanged with electronic multipliers, the processors of FIGS. 5 and 6 are very flexible and can be used for dynamic processing, as where it is desired to perform different types of processing as a function of time.

The two-dimensional correlators of FIGS. 5 and 6 can be used to implement a two-dimensional spectrum analyzer. The processor will take the Fourier transform of a time-varying input signal to provide a coarse frequency vs fine frequency output. Such an analyzer can provide a large array of filter elements (typically 10^{5} to 10^{6}) over wide bandwidths. The advantage of the time-integrating architecture in this case is that the resolution and bandwidth can be scaled electronically. In addition, the two-dimensional correlators of FIGS. 5 and 6, or the moving mirror processor of FIG. 2, can be used to provide either a two-dimensional transform or ambiguity processor without modification to the optics.

Consider the time-integrating correlator used to implement the Fourier transform by the chirp algorithm. Let [See equation in original](16)

where

S(t) = signal to be transformed

omega [o] = carrier frequency

a = angular acceleration of the chirp,

and [See equation in original](17)

where g(t) is the same chirp used to modulate S(t). The change in sign of the exponential comes from using the negative first-order diffraction rather than the positive order. The output light amplitude at the detector, using a reference wave Ae<j alpha x >is [See equation in original](18)

The corresponding intensity is [See equation in original](19)

The detector integrates this intensity and produces an output proportional to [See equation in original](20)

This is the Fourier transform of S(t). The transform is on a spatial carrier (omega [o]/v) and has a phase distortion (x/v)<2>a/2. Such phase distortion is characteristic of the chirp transform. This one-dimensional spectrum analyzer can be considered as the product of S(t) and a set of oscillators running at frequency ax/v. Each product is then integrated on the detector.

If the chirps are repeated with a period T, then only local oscillators of frequency n/T (n = 0,1,2 . . .) exist. If the detector integrates for a period KT, then any frequency that deviates from a multiple of 1/T by more than 1/KT Hz will not produce a significant output. That is, the difference frequency will oscillate more than one cycle over the integration period KT. This means the output is a comb filter with passbands of width 1/KT and spaced 1/T apart. The spaces between the teeth of the comb can be filled in, as in the ambiguity processor, by a second distributed local oscillator covering the band from 0 to 1/T in frequency and orthogonal in space to the first. This leads to the two-dimensional spectrum analyzer.

Any of the three-product processors of FIGS. 2, 5 or 6 can be used to implement the two-dimensional spectrum analyzer, by providing the processor with the appropriate inputs. For example, using the processor of FIG. 5, let f[x](t) and g[x](t) be given by equations (16) and (17) respectively. Further, let f[y](t) = g[y](t) be a slower chirp, [See equation in original](21)

having a period equal to KT, the integration time. As previously described, this produces a distributed local oscillator in the orthogonal, vertical, dimension, which covers the band 0 to 1/T in frequency.

The output of the spectrum analyzer for the input signal S(t) will be in a raster format, with the fine frequency axis in the y dimension, along discrete coarse frequency lines spaced in the x dimension. Each point (x, y) on a line contains the spectral component at frequency 1/v(ax + a2y). The fine frequency resolution is 1/KT with a range of a2T'/2 Hz, where T' is the time aperture or delay of the acousto-optic modulators. The separation between coarse frequency lines is 1/T. In order that the spectrum be presented without "holes" or redundancy, the fine frequency range should equal the coarse line separation. Similarly, the coarse frequency range is a T'/2 pi Hz.

KT > > T, B >/= aT/2 pi , and B >/= a2KT/2 pi ,

where B is the bandwidth of the acousto-optic modulators. Practically, the number of resolution elements is limited by the number of detector cells.

To illustrate the spectrum analyzer, assume an input frequency of 1.5/T. This will beat with the horizontal local oscillator running at 1/T to produce a difference of 0.5/T. This difference will then mix with the 0.5/T vertical local oscillator to produce a DC output that will build up on the integrator. The output format is shown in FIG. 7. Both axes now represent frequency. A change in frequency of 1/T causes the output to step one element in the horizontal dimension. A change in frequency equal to the reciprocal of the detector integration time causes the output to step one resolution element in the vertical dimension.

It should be emphasized that the optical architecture of the two-dimensional spectrum analyzer is identical to the ambiguity function processor, only the electronic nature of the signals need be changed to alter the cross ambiguity processor to the two-dimensional spectrum analyzer. Similarly, by supplying appropriate inputs, the two-dimensional optical processors can perform a variety of processing operations. It should also be obvious to those skilled in the art that, in most cases, it makes little difference into which modulators the various signals are input, or whether the multiplications take place electronically in mixers or in the detector, or optically in the light modulators.

In addition, while the differences in optical architecture between the processors of FIGS. 2, 5 and 6 may offer some economies in terms of components, in general, the processing capabilities of the different architectures are the same. As previously explained, the processors of FIGS. 5 and 6 are basically the same. The processor of FIG. 6 simply substitutes an electronic multiplication for an optical multiplication, and performs all optical multiplications "in line" on the same optical beam. Light modulator 72, could equally as well have been left in the same position as illustrated in FIG. 5, while still combining f[x](t) and f[y](t) in modulator 75 to eliminate light modulator 71. Similarly, the moving mirror of the processor of FIG. 2 could equally as well have been used to impose a linearly varying frequency shift on the modulated light beam from light modulator 12 directly, by repositioning it to receive the diffracted light from modulator 12, and repositioning the detector to receive the reflected light from the mirror. However, since it would have still been necessary to provide a reference beam to the detector, a stationary mirror would also have been required. Accordingly, the architecture of FIG. 2 is a bit more efficient in its use of optical components. The processing capabilities of the two architectures are the same, however.

While the foregoing has been with reference to specific embodiments, it will be appreciated by those skilled in the art that numerous variations are possible without departing from the invention. It is intended that the invention be limited only by the appended claims.

CLAIMS: What is claimed is:

[*1] 1. A time-integrating optical processor comprising:

a light beam;

a two-dimensional time-integrating detector;

means for modulating the light beam in a first spatial dimension, x, said x-modulating means including a first one-dimensional spatial light modulator;

means for expanding the x-modulated beam in a second, mutually orthogonal spatial dimension, y;

means for modulating the light beam in the second spatial dimension, said y-modulating means including a second one-dimensional spatial light modulator; and

means for imaging said expanded x-modulated and said y-modulated light beams onto the detector.

[*2] 2. The optical processor of claim 1 wherein said first spatial light modulator comprises:

a first acousto-optic light modulator for modulating said light beam with a first signal f[x](t); and

a second acousto-optic light modulator for modulating the light beam from said first acousto-optic modulator with g[x](t - x/v), where v is the velocity of sound propagation in said second acousto-optic modulator in said first spatial dimension, x, and g[x](t) is a second signal input to said second acoustic-optic modulator, thereby providing a light beam having an amplitude variation of f[x](t) g[x](t - x/v) in said x dimension.

[*3] 3. The optical processor of claim 2, wherein said second spatial light modulator comprises means for modulating said light beam in said second spatial dimension, y, with a continuously distributed local oscillator signal.

[*4] 4. The optical processor of claim 3, wherein said second spatial light modulator is a scanning mirror having small linear rotations about an axis parallel to said first spatial dimension, x, such that said light beam is reflected from said mirror with a linearly varying frequency shift in said y dimension.

[*5] 5. The optical processor of claim 2 wherein said second spatial light modulator comprises a third acousto-optic light modulator for modulating said light beam in said second spatial dimension, y, with g[y](t - y/v), where v is the velocity of sound propagation in said third acousto-optic modulator in said second spatial dimension, y, and g[y](t) is a third signal input to said third acousto-optic modulator.

[*6] 6. The opticl processor of claim 5 wherein said second spatial light modulator further comprises a fourth acousto-optic light modulator for modulating said light beam with a fourth signal, f[y](t), thereby providing a light beam having an amplitude variation of f[y](t) g[y](t - y/v) in said y dimension, said optical processor being a two-dimensional correlator.

[*7] 7. The optical processor of claim 6 wherein said signals f[y](t) and g[y](t) are chirp signals, thereby providing a distributed local oscillator in said y dimension.

[*8] 8. The optical processor of claims 4 or 6 wherein said means for modulating said light beam in mutually orthogonal spatial dimensions further comprises means for splitting said light beam into first and second light beams, said first and second light beams modulating by said first and second spatial light modulators, respectively, and wherein said optical processor further comprises means for imaging and combining said first and second light beams on said time-integrating detector.

[*9] 9. The optical processor of claims 3 or 7 wherein said first signal, f[x](t), is an information signal to be processed; said second signal, g[x](t), is a predetermined reference signal and said processor is a two-dimensional ambiguity function processor.

[*10] 10. The optical processor of claim 2 wherein said first signal [See equation in original]

where S(t) is an information signal to be processed and [See equation in original]

is a chirp signal having a carrier frequency of omega [o]and an angular acceleration of a; and said second signal g[x](t) is a chirp signal, [See equation in original]

[*11] 11. The optical processor of claim 10 further comprising:

means for repeating said chirps with a period of T seconds; and

wherein said second spatial light modulator includes means for modulating said second beam of light in said spatial dimension y, with a distributed local oscillator having a continuous frequency distribution between 0 and 1/T, thereby providing a two-dimensional spectrum analyzer.

[*12] 12. The optical processor of claim 1 wherein said first one-dimensional spatial light modulator comprises:

an electronic modulator for generating a first signal h(t) as the product between second and third signals, f[x](t) and f[y](t);

a first acousto-optic light modulator for modulating said light beam with said signal h(t);

a second acousto-optic light modulator for modulating said light beam with g[x](t - x/v), where v is the velocity of sound propagation in said second acousto-optic light modulator in said first spatial dimension, x, and g[x](t) is a fourth signal input to said second acousto-optic modulator; and wherein said second one-dimensional spatial light modulator comprises:

a third acousto-optic light modulator for modulating said light beam with g[y](t - y/v), where v is the velocity of sound propagation in said third acousto-optic modulator in said second spatial dimension, y, and g[y](t) is a fifth signal input to said third acousto-optic modulator, thereby providing a light beam having an amplitude variation of h(t)g[x](t - x/v)g[y](t - y/v).

[*13] 13. The optical processor of claim 12 wherein the type of processing performed by said optical processor is determined by the selection of said signals f[x](t), f[y](t), g[x](t), and g[y](t).

[*14] 14. A time-integrating optical processor, comprising:

a light beam;

means for splitting said light beam into first and second light beams;

a first acousto-optic light modulator for modulating said first light beam with a first signal, f(t);

first spreading means for spreading the modulated light beam from said first acousto-optic modulator in a first spatial dimension, x;

a second one-dimensional acouto-optic light modulator for modulating said spread light beam from said first acousto-optic modulator in said first spatial dimension, x, with a second signal g(t);

second spreading means for spreading the diffracted light from said second acousto-optic modulator in a second spatial dimension, y, orthogonal to said first spatial dimension, x;

a scanning mirror having small linear rotations about an axis parallel to said x dimension for reflecting said sec light beam from said mirror with a linearly varying frequency shift in said y dimension; and

a two-dimensional time-integrating detector for detecting said light beams from said second spreading means and from said scanning mirror.

[*15] 15. The optical processor of claim 14 wherein said signal g(t) is a time-delayed and frequency shifted replica of f(t) and said optical processor is an ambiguity function processor for detecting and providing an output signal representative of said time delay and frequency shift.

[*16] 16. The optical processor of claims 2, 5, 6, 12 or 14, wherein said acousto-optic light modulators are Bragg cell modulators.

Pat. No. 4474434 printed in FULL format.

4,474,434

<=2> GET 1st DRAWING SHEET OF 2

Oct. 2, 1984

Polarization-insensitive optical switch apparatus

INVENTOR: Carlsen, W. John, Boston, Massachusetts
Melman, Paul, Newton, Massachusetts

ASSIGNEE-AT-ISSUE: GTE Laboratories Incorporated, Waltham, Massachusetts (02)

APPL-NO: 327,873

FILED: Dec. 7, 1981

CERTCORR: Corrections in Certificate of Correction dated Jun. 30, 1987 are entered herein. This certificate also contains corrections to data that is not reproducible in LEXPAT.

INT-CL: [3] G02F 1#03

US-CL: 350#381; 350#388

CL: 350

SEARCH-FLD: 350#383, 381, 380, 382, 388

REF-CITED:

U.S. PATENT DOCUMENTS

3,499,701	3/1970	Macek et al.	350#380
3,632,187	1/1972	Habegger	350#381

PRIM-EXMR: Arnold, Bruce Y.

LEGAL-REP: Fisher; Fred

CORE TERMS: beam, crystal, polarized, polarization, spot, splitter, perpendicularly, path, rotating, optical, rotated, oriented, input, switch, ninety, fiber, refraction, coupled, coating, wave, splitting, reflective, polarization-insensitive, electro-optical, electrodes, collimated, dielectric, multimode, traverse, prism

ABST:
Polarization-insensitive optical switch and dual channel carrier multiplexer includes a polarization beam splitter for receiving an input collimated beam which has arbitrarily polarized components, splitting the beam into the two components. One of the components is rotated by a 1/2 wave plate so as to yield a polarized beam which is polarized in the same direction as the other beam. The two polarized beams are then applied to a polarization sensitive interferometric multimode fiber optic switch and modulator. The output of the interferometric multimode fiber optic switch and modulator contains two beams, both polarized in the same direction. One of the beams is rotated ninety degrees by a [178] 1/2

wave plate, and the two mutually perpendicularly polarized beams are then recombined by a polarization beam splitter operated in reverse to yield an output beam containing mutually perpendicular components.

NO-OF-CLAIMS: 4

EXMPL-CLAIM: <=5> 1

NO-OF-FIGURES: 6

NO-DRWNG-PP: 2

SUM:

BACKGROUND OF THE INVENTION

1. Field of the Invention

This invention relates to polarization-insensitive optical switch apparatus, polarization-insensitive optical multiplexing apparatus, and interferometric multimode fiber optic apparatus in which the indices of refraction of various beam paths through portions thereof can be varied with respect to that of other portions. Accordingly, it is the general object of this invention to provide new and improved apparatus of such character.

2. Decription of the Prior Art

Polarization-insensitive switching of multimode fibers has been achieved by means of mechanical switches which move an input fiber into alignment with two output fibers, at two stable positions.

Electronic carrier multiplexing of two optical signals has been accomplished. Usually, the multiplexing stage is performed electronically; the resulting signal modulates the current through a light source. The drive currents [to] of two different light sources can be modulated, and the two signal carrying fibers can be combined into a single communication fiber by means of a fiber combiner.

Disadvantageously, mechanical switching is slow, is power consuming, is usually operated at high voltages, is cumbersome, and is unreliable.

Disadvantageously, the multiplexing techniques (in which a single light source is modulated by the already multiplexed signal) requires very high linearity of the modulated source in order to prevent crosstalk. The light sources used in communication systems have nonuniform, nonlinear responses, sufficient to make this method inapplicable in many cases.

The modulation of the drive currents of two different light sources, utilizing an optical combiner, disadvantageously has at least a 50%, or 3 dB, loss due to the principle of combination of two light beams. Typical losses described in the literature are approximately 4 dB.

SUMMARY OF THE INVENTION

It is another object of this invention to provide a new and improved polarization-insensitive optical fiber switch and dual channel carrier multiplexer.

Yet another object of this invention is to provide a new and improved optical switch apparatus in which operation is very fast compared to mechanical switching.

Still another object of this invention is to provide a new and improved low-loss device for optical switching and optical multiplexing which is polarization-insensitive.

Devices in accordance with this invention are of a low-loss nature due to the collimating optics and the large aperture of an interferometric multimode fiber optic switch and modulator, such as that described in our copending U.S. application Ser. No. 317,362, filed [Nov. 4, 1981] Nov. 2, 1981 and entitled "INTERFEROMETRIC MULTIMODE FIBER OPTIC SWITCH AND MODULATOR". Its polarization-insensitivity facilitates the apparatus for use with unpolarized light sources, such as LEDs. In a multiplexing configuration, the light source linearity problem and the combiner losses are eliminated. Its complementary output provides a second channel (or a monitoring signal) without the interruption of the light beam.

Still another object of this invention is to provide a new and improved polarization-insensitive electro-optical switch for use with multimode fibers.

Yet another object of this invention is to provide a new and improved modulator which can modulate two polarizations of an unpolarized light source with different signals.

Still yet another object of this invention is to provide a new and improved apparatus for multiplexing in which the 3 dB loss from the beam recombination process in a two signal multiplexing scheme can be eliminated.

Yet still another object of this invention is to provide for a polarization-insensitive fast multimode optical fiber switch or modulator, or a dual channel electronic carrier frequency multiplexer using a single light source and single fiber, in which, when operated in a switch mode, polarization losses inherent in electro-optical devices are eliminated, and when operated in a multiplexer mode, losses inherent in optical combiners due to basic optic restrictions are eliminated.

In accordance with one embodiment of the invention, a polarization-insensitive optical switch apparatus for switching a collimated input beam between two output means comprises a first polarization beam splitter for receiving and splitting the collimated input beam into two perpendicularly polarized beams. A first polarization rotating means rotates a first of the two perpendicularly polarized beams by ninety degrees so that the rotated beam and a second of the perpendicularly polarized beams are each polarized in the same direction. One of the first and the second beams is reflected so that the reflected beam and the other of the first and second beams traverse parallel paths. A first electro-optical crystal has a first surface adapted to receive the reflected one beam and the other beam for transmission therethrough. The first crystal contains a second surface which is adapted to receive the transmitted beams from the first surface thereof at a first pair of spots. The

crystal further contains a first reflective surface which is oriented to receive light beams from the first pair of spots and to reflect such light beams. The crystal further has a third surface which is adapted to receive the reflected light beams from the first reflective surface of the first crystal upon a second pair of spots. The crystal further contains a fourth surface which is adapted to externally pass light beams impinged thereupon from the second pair of spots. A second electro-optical crystal has a first surface. The second crystal further has a second surface which is oriented to receive transmitted light from the second surface of the first crystal at a first pair of spots. The second crystal further contains a first reflective surface which is oriented to receive light from the first pair of spots of the second surface of the second crystal and to reflect such received light. The second crystal further contains a third surface which is adapted to receive the reflected light from the first reflective surface of the second crystal upon a second pair of spots, the second crystal having a fourth surface which is adapted to externally pass light beams impinged thereupon from the second pair of spots of the second crystal. The embodiment further includes a dielectric beam splitting coating. The beam splitting coating and the two crystals are so oriented that the first pairs of spots of the two crystals are substantially juxtaposed with a first portion of the coating oriented therebetween. The second pairs of spots of the two crystals are substantially juxtaposed with a portion of the coating oriented therebetween. The index of refraction of one of the crystals can be varied with respect to that of the other. Means are associated with the fourth surface of the first crystal for reflecting one light beam from one spot of the second pair of spots thereof. A second polarization rotating means rotates a first of the light beams from the fourth surface of the first crystal by ninety degrees so that the rotated first light beam and the unrotated second light beam are mutually perpendicularly polarized. A second polarization beam splitter, which is operated in reverse, is coupled to receive the perpendicularly polarized output beams from the first crystal and to provide a first single light beam which can be coupled to a first optical output means. Means are associated with the fourth surface of the second crystal for reflecting one light beam from one spot of the second pair of spots thereof. A third polarization rotating means rotates a first of the light beams from the fourth surface of the second crystal by ninety degrees so that the rotated first light beam and the unrotated second beam, from the second crystal, are mutually perpendicularly polarized. A third polarization beam splitter, which is operated in reverse, is coupled to receive the perpendicularly polarized output beams from the second crystal, and to provide a second single light beam which can be coupled to a second optical output means.

In accordance with still another object of the invention, polarization-insensitive optical switch apparatus for switching a pair of collimated input beams between two output means includes a first polarization beam splitter for receiving and splitting one of the collimated input beams into two perpendicularly polarized beams. A first polarization rotating means rotates a first of the two perpendicularly polarized beams by ninety degrees so that the rotated polarized beam and a second of the perpendicularly polarized beams are each polarized in the same direction. One of the first and the second beams is reflected so that the reflected beam and the other of the first and the second beams traverse parallel paths. A first electro-optical crystal has a first surface adapted to receive the reflected one beam and the other beam for transmission therethrough. The first crystal further has a second surface which is adapted to receive transmitted beams from the first surface at a first pair of spots. The first crystal has a first reflective surface which is oriented to receive light beams from the first pair of spots and to reflect such light

beams, the first crystal further having a third surface adapted to receive the reflected light beams from the first reflective surface thereof upon a second pair of spots. The first crystal further has a fourth surface which is adapted to externally pass light beams impinged thereupon from the second pair of spots. The embodiment further includes second means associated with the fourth surface of the first crystal for reflecting one light beam from one spot of the second pair of spots. A second polarization rotating means rotates the first of the light beams from the fourth surface of the first crystal by ninety degrees so that the rotated first light beam and the unrotated second light beam are perpendicularly polarized with respect to each other. A second polarization beam splitter, which is operated in reverse, is coupled to receive the perpendicularly polarized output beams from the first crystal, and to provide a first single light beam which can be coupled to a first optical output means. A third polarization beam splitter receives and splits the other of the collimated input beams into two perpendicularly polarized beams. A third polarization rotating means rotates a first of the two perpendicularly polarized beams from the third polarization beam splitter by ninety degrees so that the rotated beam and a second of the perpendicularly polarized beams from the third polarization beam splitter are each polarized in the same direction. A third means reflects one of the first and the second beams from the third polarization rotating means so that the reflected beam and the other of the first and the second beams from the third polarization rotating means traverse parallel paths. A second electro-optical crystal has a first surface which is adapted to receive the one beam reflected by the third means and the other beam from the third polarization rotating means for transmission through the second crystal. The second crystal has a second surface which is adapted to receive the transmitted beams from the first surface of the second crystal at a third pair of spots, the second crystal having a first reflective surface which is oriented to receive light beams from the third pair of spots of the second surface thereof and to reflect such light beams. The second crystal further has a third surface adapted to receive such reflected light beams from the first reflective surface thereof upon a fourth pair of spots, and a fourth surface adapted to externally pass light beams impinged thereupon from the fourth pair of spots thereof. The embodiment further contains a dielectric beam splitting coating. The coating, the first crystal, and the second crystal are so oriented that the first pair of spots of the second surface of the first crystal, and the third pair of spots of the second crystal are substantially juxtaposed with a first portion of the coating oriented therebetween; a second pair of spots of the first crystal and a fourth pair of spots of the second crystal are substantially juxtaposed with a second portion of the coating oriented therebetween. Means are provided for varying the index of refraction of one of the crystals with respect to that of the other. Fourth means, associated with the fourth surface of the second crystal, reflect one light beam from one of the fourth pair of spots of the second crystal. A fourth polarization rotating means rotates a first of the light beams from the fourth surface of the second crystal by ninety degrees so that the rotated first light beam from the second crystal and the unrotated second light beam from the second crystal are mutually perpendicularly polarized. A fourth polarization beam splitter, which is operated in reverse, is coupled to receive the perpendicularly polarized output beams from the second crystal and to provide a second single output light beam which can be coupled to a second optical light means.

In accordance still yet with another embodiment of the invention, polarization-insensitive optical multiplexing apparatus for independently modulating perpendicularly polarized components of a collimated input beam

includes a first polarization beam splitter for receiving and splitting the input beam into two perpendicularly polarized beams. A first polarization rotating means rotates a first of the two perpendicularly polarized beams by ninety degrees so that the rotated polarized beam and a second of the perpendicularly polarized beams are each polarized in the same direction. Means are provided for reflecting one of the first and the second beams so that the reflected beam and the other of the first and the second beams traverse parallel paths. A first electro-optical crystal has a first surface which is adapted to receive the reflected one beam and the other beam for transmission therethrough. The first crystal has a second surface which is adapted to receive such transmitted beams from the first surface at a first pair of spots. The first crystal has a first reflective surface which is oriented to receive light beams from the first pair of spots and to reflect such light beams. The first crystal further has a third surface adapted to receive such reflected light beams from the first reflective surface of the first crystal upon a second pair of spots; the first crystal has a fourth surface adapted to externally pass light beams impinged thereupon from the second pair of spots of the first crystal. The embodiment further includes a second electro-optical crystal which has a first surface and which has a second surface oriented to receive transmitted light from the second surface of the first crystal at a first pair of spots. The second crystal has a first reflective surface oriented to receive light from the first pair of spots of the second surface thereof and to reflect such received light. The second crystal further contains a third surface which is adapted to receive such reflected light from the first reflective surface thereof upon a second pair of spots. The second crystal further has a fourth surface which is adapted to externally pass light beams impinged thereupon from the second pair of spots thereof. The embodiment further contains a dielectric beam splitting coating wherein the coating, the first crystal, and the second crystal are so oriented that the first pairs of spots of the second surfaces of the two crystals are substantially juxtaposed with the first portion of the coating oriented therebetween. Second pairs of spots of the third surfaces of the two crystals are substantially juxtaposed with a second portion of the coating oriented therebetween. One beam and the other beam traverse a first and a second path, respectively, within the first crystal. One beam and the other beam traverse a third path and a fourth path, respectively, within a second crystal. The index of refraction of the first path within the first crystal is varied with respect to that of the third path within the second crystal. Also, the index of refraction of the second path within the first crystal is varied with respect to that of the fourth path within the second crystal, the variation of the indices of refraction being independent of each other. Means, associated with the fourth surface of the first crystal, reflect one light beam from one spot of the second pair of spots thereof. A second polarization rotating means rotates a first of the light beams from the fourth surface of the first crystal by ninety degrees so that the rotated first light beam and the unrotated second light beam are perpendicularly polarized with respect to each other. A second polarization beam splitter, operated in reverse, is coupled to receive the perpendicularly polarized light beams from the first crystal and to provide a first single light beam which can be coupled to a first optical output means. In accordance with certain features of the invention, the foregoing embodiment can include, in association with the fourth surface of the second crystal, means for reflecting one light beam from one spot of the second pair of spots of the second crystal. A third polarization rotating means rotates a first of the light beams from the fourth surface of the second crystal by ninety degrees so that the rotated first light beam and the unrotated second beam, from the second crystal, are mutually perpendicularly polarized. A third polarization beam

splitter, operated in reverse, receives the perpendicularly polarized output beams from the second crystal and provides a second single light beam which can be coupled to a second optical output means.

In accordance with still yet another embodiment of the invention, a polarization-insensitive optical multiplexing apparatus for independently modulating perpendicularly polarized components of a pair of collimated input beams includes a first polarization beam splitter for receiving and splitting one of the input beams into two perpendicularly polarized beams. A first polarization rotating means rotates a first of the two perpendicularly polarized beams by ninety degrees so that the rotated polarized beam and a second of the perpendicularly polarized beams are each polarized in the same direction. A first means is provided for reflecting one of the first and the second beams so that the reflected beam and the other of the first and the second beam traverse parallel paths. A first electro-optical crystal has a first surface which is adapted to receive the reflected one beam and the other beam for transmission therethrough. The first crystal has a second surface which is adapted to receive the transmitted beams from the first surface thereof at a first pair of spots. The first crystal further has a first reflective surface which is oriented to receive light beams from the first pair of spots of the second surface thereof and to reflect such light beams. The first crystal further has a third surface which is adapted to receive the reflected light beams from the first reflective surface thereof upon a second pair of spots. The first crystal further has a fourth surface adapted to externally pass light beams impinged thereupon from the second pair of spots thereof. Thus, the one beam and the other beam traverse a first path and a second path, respectively, within the first crystal. Second means, associated with the fourth surface of the first crystal, reflect one light beam from one spot of the second pair of spots thereof. A second polarization rotating means rotates a first of the light beams from the fourth surface of the first crystal by ninety degrees so that the rotated first light beam and the unrotated second light beam are mutually perpendicularly polarized. A second polarization beam splitter, operated in reverse, is coupled to receive the perpendicularly polarized output beams from the first crystal and to receive a first single light beam which can be coupled to a first optical output means. A third polarization beam splitter receives and splits the other collimated input beam into two perpendicularly polarized beams. A third polarization rotating means rotates a first of the two perpendicularly polarized beams from the third polarization beam splitter by ninety degrees so that the rotated beam and a second of the perpendicularly polarized beams from the third polarization beam splitter are each polarized in the same direction. Third means reflects one of the first and the second beams from the third polarization rotating means so that the reflected beam and the other of the first and second beams from the third polarization rotating means traverse parallel paths. A second electro-optical crystal has a first surface which is adapted to receive one beam reflected by the third means and the other beam from the third polarization rotating means for transmission through the second crystal. The second crystal has a second surface adapted to receive such transmitted beams from the first surface thereof at a third pair of spots. The second crystal has a first reflective surface oriented to receive light beams from the third pair of spots of the second surface thereof and to reflect such light beams. The second crystal has a third surface adapted to receive such reflected light beams from the first reflective surface thereof upon a fourth pair of spots; the second crystal has a fourth surface adapted to to [externallly] externally pass light beams impinged thereupon from the fourth pair of spots thereof. Thus, one beam reflected by the third means and the other beam from the third polarization

rotating means traverse a third path and a fourth path, respectively, within the second crystal. A dielectric beam splitting coating, the first crystal, and the second crystal are so oriented that the first pair of spots of the first crystal and the third pair of spots of the second crystal are substantially juxtaposed with a first portion of the coating oriented therebetween. The second pair of spots of the third surface of the first crystal and the fourth pair of spots of the second crystal are substantially juxtaposed with a second portion of the coating oriented therebetween. First means vary the index of refraction of the first path within the first crystal with respect to that of the third path within the second crystal. In similar fashion, second means vary the index of refraction of the second path within the first crystal with respect to that of the fourth path within the second crystal. Fourth means, associated with the fourth surface of the second crystal, reflects one light beam from one spot of the fourth pair of spots of the second crystal. A fourth polarization rotating means rotates a first of the light beams from the fourth surface of the second crystal by ninety degrees so that the rotated first light beam from the second crystal and the unrotated second light beam from the second crystal are perpendicularly polarized with respect to each other. A fourth polarization beam splitter, operated in reverse, is coupled to receive the perpendicularly polarized light beams from the second crystal and provides a second single output light beam which can be coupled to a second optical output means.

In accordance with still yet another embodiment of the invention, a combination includes a dielectric beam splitting coating which is affixed to portions of a first and a second electro-optical crystals with portions of crystals being juxtaposed. First means vary the index of refraction of one beam path through one of the crystals with respect to that of one beam path through the other. Second means vary the index of refraction of another beam path through one of the crystals with respect to that of another beam path through the other. The second means is independent from the first means. In accordance with certain features of the invention, the first means comprises a first set of electrodes deposited upon opposite portions of the crystals so as to encompass the one beam paths and the second means comprises a second set of electrodes deposited upon opposite portions of the crystals so as to encompass the other beam paths. The two sets of electrodes can be independent of each other.

In accordance with another embodiment of the invention, polarization-insensitive optical switching apparatus for switching a collimated input beam between two output conductors includes a first polarization beam splitter for receiving and splitting the input beam into two perpendicularly polarized beams. A first polarization rotating means rotates a first of the two perpendicularly polarized beams by ninety degrees so that the rotated polarized beam and a second of the perpendicularly polarized beams are each polarized in the same direction. Suitable means reflects one of the first and the second beams so that the reflected beam and the other of the first and the second beams traverse parallel paths. Polarization-sensitive interferometric multimode fiber optic switch means receives the reflected beam and the other beam at one input thereof, and selectively provides the reflected beam and the other beam at a first pair of outputs and at a second pair of outputs. Means associated with the first pair of outputs reflect a beam selected from the reflected beam and the other beam. A second polarization rotating means rotates a first of the light beams from the first pair of outputs by ninety degrees so that the rotated first light beam and the unrotated second light beam are mutually perpendicularly polarized. A second polarization beam splitter, operated in reverse, receives the perpendicularly polarized output beams and provides a first single light

beam which can be coupled to a first optical output means. Means associated with the second pair of outputs reflect a beam selected from the reflected beam and the other beam. A third polarization rotating means rotates a first of the light beams from the second pair of outputs by ninety degrees so that the rotated first light beam and the unrotated second light beam from the second pair of outputs are perpendicularly polarized with respect to each other. A third polarization beam splitter, operated in reverse, receives the perpendicularly polarized output beams from the second pair of outputs, and provides a second single light beam which can be coupled to a second optical output means. In accordance with certain features of the invention, the index of refraction for one portion of the polarization-sensitive interferometric multimode fiber optic switch means is variable from that of a second portion thereof. The reflected one beam can traverse a first path and a second path within a first portion and a second portion, respectively, of the polarization-sensitive interferometric multimode fiber optic switch means. The other beam can traverse a third path and a fourth path within a third portion and a fourth portion, respectively, of the polarization-sensitive interferometric multimode fiber optic switch means. The index of refraction of the first portion can be varied from that of the second portion. The index of refraction of the third portion can be varied from that of the fourth portion.

DRWDESC:
BRIEF DESCRIPTION OF THE DRAWING

Other objects and features of this invention, together with its construction and mode of operation, will become more apparent from the following description, when read in conjunction with the accompanying drawing, in which:

FIG. 1 is a schematic diagram of one embodiment of this invention;

FIG. 2 is a modular version of the embodiment shown in FIG. 1;

FIG. 3 is a "p" polarization version of the modulator embodiment depicted in FIG. 2;

FIG. 4 is a plan view of another embodiment of the invention utilizing an IMFOS, as described in greater detail hereinafter, the dotted lines illustrating an outline of electrodes applied to such IMFOS;

FIG. 5 is a plan view of still another embodiment of the invention, utilizing a modified IMFOS which uses rectangular shape crystals with individual electrodes being depicted in dotted line format; and

FIG. 6 is a cross-sectional view of the embodiment shown in FIG. 4, taken along the line 6-6 thereof.

DETDESC:

DESCRIPTION OF PREFERRED EMBODIMENTS

A polarization-insensitive optical switch and dual channel carrier multiplexer, in accordance with this invention, utilizes the interferometric multimode fiber optic switch (IMFOS) described in a copending patent application by the applicants hereof, entitled "Interferometric Multimode Fiber Optic Switch and Modulator" U.S. application Ser. No. 317,362, filed Nov. 4, 1981. Broadly,

an IMFOS, as described in the above-identified application, includes a dielectric beam splitting coating affixed to portions of two electro-optical crystals with coated portions of the crystals being juxtaposed. The index of refraction of one of the crystals is varied with respect to that of the other.

The teachings of the copending application are incorporated herein by reference.

Referring to FIG. 1, an IMFOS 11 is represented schematically as a rectangle. The IMFOS 11 is similar to that described in the copending application in which a beam path is modulated in accordance with an electrical field applied thereto. By the application of particular fields, a light beam is switched on and off or is modulated at varying intensities. The IMFOS 11, as depicted in FIG. 1 is polarization sensitive, and light of one polarity only is normally handled therethrough. In the embodiment depicted in FIG. 1, light, which is s plane polarized, is conveniently handled.

A collimated input beam 12 either can be unpolarized or can contain arbitrarily polarized light beams therewithin. The input beam 12 is split into two perpendicularly polarized beams, a p beam and an s beam, by a polarization beam splitter 13. The polarization beam splitter 13 can be constructed of birefrigent prisms, such as, for example, Rochon prisms, or multilayer interference polarizers.

The p polarized beam passes through a 1/2 wave plate 14 which converts it into an s polarized beam. The s polarized beam, split by the polarization beam splitter 13, is reflected by a mirror 16 so that it, and the s polarized beam emitted from the 1/2 wave plate 14, traverse parallel paths and enter the IMFOS 11.

The two s polarized beams that enter the IMFOS 11 undergo an interference and intensity redistribution as described more fully in the above-identified pending application.

As depicted in FIG. 1, the s polarized beam (which exited from the 1/2 wave plate 14 through the IMFOS 11) is reflected by a mirror 17 to another polarization beam splitter 18 which is operated in reverse. The s polarized beam, which had been reflected by the mirror 16 and past through the IMFOS 11, is rotated by a 1/2 wave plate 19 into a p polarized beam. The p polarized beam from the 1/2 wave plate 19 and the s polarized beam from the mirror 17 are recombined by the polarization beam splitter 18 (which operates in reverse) to provide an output signal or output beam 21 which contains mutually perpendicular polarized beams p and s.

A modulator version of the embodiment shown in FIG. 1, is depicted in FIG. 2. A collimated input beam 12 contains either mutually perpendicularly polarized beams p and s, or it can contain unpolarized light. The beam 12 is applied through a polarization beam splitter 13, as before, which reflects a portion of the beam to a prism 26 which reflects the s polarized portion thereof toward the IMFOS 11. That portion of the beam 12 which passes through the polarization beam splitter 13 is emitted therefrom as a p polarized beam. The p polarized beam is rotated ninety degrees by the 1/2 wave plate 14. Thus, the prism 26 send an s polarized beam to the IMFOS 11 and the 1/2 wave plate 14 sends an s polarized beam to the IMFOS 11. The s polarized beam from the 1/2 wave plate 14, which passes through the IMFOS 11, is reflected by another prism 37 to a

polarization beam splitter 18 which is operated in reverse. The s polarized beam (which had been reflected by the prism 26) passes through the IMFOS 11 and is rotated ninety degrees by the 1/2 wave plate 19 into a p polarized beam. The p polarized beam passes through the polarization beam splitter 18 and the s polarized beam from the prism 37 is reflected by the polarization beam splitter 18 (which operates in reverse) so that the output 21 contains both the p and the s mutually perpendicular beams.

FIG. 3 depicts a p polarization version of that described in FIG. 2. A collimated input beam 12, as before, is either unpolarized or contains mutually perpendicularly polarized beams. The input beam 12 is applied to a polarization beam splitter 13, as before. A p polarization portion of the beam passes directly from the polarization beam splitter 13 to an IMFOS 11, passing therethrough. The s polarized beam, reflected by the polarization beam splitter 13, passes through a 1/2 wave plate 34 which converts the s polarized beam into a second p polarized beam which, in turn, is reflected by a prism 36. The p polarized beam, reflected by the prism 36, passes through the IMFOS 11 and, then passes through a polarization beam splitter 38, which operates in reverse. The p polarized beam from the polarization beam splitter 13, which passes through the IMFOS 11, is reflected by a prism 40, and passes through a 1/2 wave plate 39 to the polarization beam splitter 38 which operates in reverse. The p polarized beam from the prism 40 is rotated ninety degrees by the 1/2 wave plate 39 to yield an s polarized beam. The s polarized beam from the 1/2 wave plate 39 is reflected by the polarization beam splitter 38 which operates in reverse to yield an output beam 41 which contains both the p and the s mutually perpendicular polarized beams.

Referring to FIG. 4, there is depicted, in plane view, an IMFOS 101 which is of general shape as that depicted in our copending application. The IMFOS 101 includes a first electro-optical crystal 102 and a second electro-optical crystal 103 which are separated by a dielectric beam splitting coating 104. The first crystal 102, the second crystal 103, and the coating 104 are so oriented with portions of them juxtaposed so that light paths from one crystal can pass through the dielectric beam splitting coating 104 into the other crystal.

Means are provided for varying the index of refraction of one of the crystals 102 with respect to that of the other crystal 103. Such means for varying the index of refraction can include electrodes 106, 107 formed on opposite sides of the crystal 103, and electrodes 108, 109 formed on opposite sides of the crystal 102. The electrodes 106, 107, 108, 109 can each be formed by depositing a layer 111 of chromium onto the respective crystals 102, 103 and, in turn, depositing individual layers of gold 112 onto the chromium layers 111. The chromium layers 111 adhere effectively to the electro-optical crystals 102, 103 and the gold layers 112 adhere effectively to the chromium layers 111. As depicted in FIG. 3, the crystallographic axes of the two crystals 102 and 103 are oriented in opposite directions. The voltages applied to the respective crystals are such that the polarities are alike in the same direction. As depicted in FIG. 6, it is positive at the top for both crystals and negative (with respect to the top) at the bottom of the two crystals. In lieu thereof, though not depicted in FIG. 6 but more fully described in the copending application, the two crystals can be oriented with their crystallographic axes in the same direction but with the voltage polarities applied in opposite directions; that is, with the crystallographic axes both directed upward, one crystal can have a positive polarity at the top and negative at the bottom, while the other crystal can have a negative polarity at the top and a positive polarity at the bottom.

An unpolarized beam of light 12, applied to the device depicted in FIG. 4, is applied to a polarization beam splitter 13. A p polarized beam from the polarization beam splitter 13 continues therethrough and is rotated by 1/2 wave plate 14 to yield an s polarized beam [16] 116. The polarization beam splitter 13 also directs an s polarized beam 117 away therefrom toward a prism 118 which reflects the s polarized beam 117 into the first electro-optical crystal 102. The s polarized beam 116, upon passing through the crystal 102, hits the dielectric beam splitter 104 at a first spot 121. The s polarized beam 117 hits the polarized beam splitter 104 at a second spot 122. The beam 116, upon hitting the spot 121, is split into two parts: 50% is reflected as a beam 216, while 50% passes through the beam splitter 104 as a beam 316 into the crystal 103. In similar fashion, the beam 117, upon hitting the spot 122 of the beam splitter 104, splits into two parts: 50% is reflected as a beam 217 while the remaining 50% passes through the beam splitter 104 as a beam 317, the beam 317 passing through the crystal 103. The beams 216, 217, which have been reflected by the beam splitter 104, remain within the crystal 102 and [is] are reflected by one surface (a reflective surface) 123 thereof down onto a second pair of spots 126, 127, respectively, so that the beam 216 can pass through the dielectric beam splitter 104 as a beam 416 or can be reflected as a beam 516, the reflected beam 516 being within the crystal 102, the beam [216] 416 being within the crystal 103. In similar fashion, the beam 217, which had been reflected by the surface 123, upon reaching the spot 127 of the beam splitter 104, passes therethrough as a beam 417 within the crystal 103 or is reflected by the beam splitter 104 as a beam 517 within the crystal 102.

The beam 416, which passes through the crystal 103, is reflected by a prism 131 to a polarization beam splitter 132 that is operated in reverse. The beam 417, an s polarized beam, exits from the crystal 103 and is rotated ninety degrees by a 1/2 wave plate 133 to a p polarized beam. The emitting p polarized beam enters the polarization beam splitter 132, which is operated in reverse so as to yield an output beam 134 which contains both p and s components.

In similar fashion, the beam 516, which exits from the crystal 102, is reflected by a prism 136 toward a polarization beam splitter 137 that is operated in reverse. The s polarized beam 517 from the crystal 102 is rotated ninety degrees by 1/2 wave plate 138 to yield a p polarized beam, which, in turn, passes through the polarization beam splitter 137. Since the polarization beam splitter 137 also emits the s polarized beam which had been reflected by the prism 136, the output beam 139 therefrom contains both p and s mutually perpendicularly polarized components of light.

As described in our copending application, referenced hereinabove, the phase velocity for a beam of light through one crystal can be changed with respect to that of another crystal by varying the index of refraction of one crystal with respect to the other. This is achieved by applying potential of appropriate polarities across the electro-optical crystals so as to cause the phase velocity for one beam path through one crystal to be different from that of a beam path through the other crystal. Hence, as depicted in FIG. 4, the entire crystal 102 can have its index of refraction varied independently of the entire crystal 103, and vice versa.

Referring to FIG. 5, there is depicted a device similar to that shown in FIG. 4 with several major changes. The device shown in FIG. 5 depicts a rectangular crystal version of an IMFOS including a first crystal 501 and a second crystal 502 adjacent to each other with a dielectric beam splitting coating 503

between their juxtaposed surfaces. A first collimated input beam 504 is applied as input A to the crystal 501. Optionally, a second input beam 506 can be applied to the crystal 502. Two possible outputs can be achieved: output A can be obtained as an output beam 507, output B can be obtained as an output beam 505.

The input collimated beams 504, 506 are unpolarized or, optionally, are beams which are mutually perpendicularly polarized. The input beams 504, 506 are applied to polarization beam splitters 507, 508, respectively. The beam splitter 507 permits a p polarized beam 510 to pass therethrough into the crystal 501. The polarization beam splitter 507 reflects a p polarized beam through a 1/2 wave plate 509 (changing it to an s polarized beam) to a prism 511 which reflects that s polarized beam 512 within the crystal 501.

In similar fashion, the optionally applied input beam 506 to the polarization beam splitter 508 passes through to the crystal 502 as an s polarized beam 513, a portion being reflected as a p polarized beam which enters a 1/2 wave plate 514 rotating it to an s polarized beam which is reflected by the prism 511 as an s polarized beam 516 which enters the crystal 502. The beams 510, 512 impinge upon the dielectric beam splitter 503 at spots 517, 518, respectively. The orientation of the components are such that beams 513, 516 impinge upon the spots 517, 518, respectively. The beams 510, 512, hitting the spots 517, 518, respectively, of the dielectric beam splitting coating 503, pass directly through (at a 50% reduction) the crystal 502 as beams 519, 521, respectively, and are reflected by the 50% beam splitter 503 (at a 50% reduction) as beams 522, 523, respectively, within the first crystal 501. Similarly, the beams 513, 516, impinging upon the spots 517, 518, pass directly through (at a 50% reduction) the dielectric beam splitting coating 503 as beams 522, 523, respectively, and are reflected (at 50% reduction) as beams 519, 521, respectively.

The beams 522, 523 are reflected at the surface 524 of the crystal 501 so that the beams 522, 523 impinge upon spots 526, 527 at the dielectric beam splitting coating 503. Likewise, the beams 519, 521, upon being reflected at the surface 528 of the crystal 502, also impinge upon the spots 526, 527 of the dielectric beam splitter 503. The reflected portions of the beams [523, 524] 522, 523 from the dielectric beam splitter 503, and the transmitted portions of the beams 519, 521 within the crystal 501, appear as beams 529, 531, respectively. In similar fashion, the transmitted components of the beams 522, 523 and the reflected components of the beams 519, 521 within the crystal 502, appear as beams 532, 533, respectively.

The s polarized beam 531 passes through the dielectric beam splitter 534 (which is operated in reverse) as an s component of the output beam 505. The s polarized beam 529 is reflected by a prism 536 to a 1/2 wave plate 537 which rotates it into a p polarized beam which is reflected by the polarization beam splitter 534 so that the output beam [508] 503 also contains a p component.

In similar fashion, the s polarized beam 533 passes through a polarization beam splitter 538 (which is operated in reverse) as an s polarized beam component of an output beam 507. The s polarized beam 532 is reflected by the prism 536 and is rotated by a 1/2 wave plate 539 to a p polarized beam to the polarization beam splitter 538 (which is operated in reverse) to reflect that p polarized beam as a component of the output beam 507. The output beam 507 contains both the p and s components.

The beam 522, as depicted in FIG. 5, traverses a path from the spot 517 (at the interface of the two crystals 501, 502) up to the top (as viewed in the drawing) surface 524 of the crystal [503] 501 and down to the spot 526 at the interface of the two crystals 501, 502. Separately, it is noted that within the same crystal 501, there is a beam path 523 from the spot 518 at the interface of the two crystals 501, 502 to [a] the top surface 504 and down to the spot 527 at the interface of the two crystals 501, 502. The paths 522, 523 are separate and distinct from each other and cross at one point as depicted in the drawing but do not interfere thereat. The index of refraction of the electro-optical crystal 501 can be varied in known fashion by varying the application of an electrical potential across the crystal. To change the index of refraction of each individual path, independent electrodes are placed across the different paths, as indicated in dotted outline. The electrodes are both at the top and the bottom of the crystal. The electrodes for the paths 522 include one set of electrodes 541A, 541B. The electrodes 541A, 541B are coupled to each electrically, but need not be performed at a surface of the crystal. In similar fashion, electrodes encompassing the path 523 can include electrodes 542A, 542B deposited at the top and bottom of the crystals encompassing the path 523. The electrodes 542A and B are coupled together.

Electrodes [542A] 543A, 543B encompass beam paths 519 from the spot 517 to the surface 528 and to the spot 526, respectively. Similarly, electrodes 544A, 544B encompass the beam path 521 from the spot 518 to the surface 528 and to the spot 527, respectively.

Thus, when the polarization-insensitive optical switch and dual channel carrier multiplexer, in accordance with this invention, is utilized as a switch, the phase retardation of both beams (that is, the entering p polarized beam and the entering s polarized beam) is identical and a single set of electrodes is used, as depicted generally in FIG. 4. When the invention is utilized as a multiplexer, each beam propagates between its own set of electrodes, as indicated in FIG. 5, and therefore can be modulated with different modulation signals. At each output port, as discussed hereinabove, there are two beams emitted, though not necessarily at the same time, and these two beams are combined utilizing a polarization beam splitter operated in reverse after one beam has past through a 1/2 wave plate. The output of the polarization beam splitter is a single light beam which can be coupled into a single fiber at each output port.

Various modifications can be performed without departing from the spirit and scope of this invention. For example, the two polarized beams, when modulated separately, need not be recombined into a single fiber. Two output focusing optics can direct each into separate output fibers.

CLAIMS: What is claimed is:

[*1] 1. Polarization-insensitive optical switch apparatus for switching a collimated input beam between two output means comprising

a first polarization beam splitter for receiving and splitting said collimated input beam into two perpendicularly polarized beams;

a first polarization rotating means for rotating a first of said two perpendicularly polarized beams by ninety degrees so that the rotated polarized beam and a second of said perpendicularly polarized beams are each polarized

in the same direction;

means for reflecting one of said first and said second beams so that the reflected beam and the other of said first and said second beams traverse parallel paths;

a first electro-optical crystal having

a first surface adapted to receive said reflected one beam and said other beam for transmission through said first crystal,

a second surface adapted to receive such transmitted beams from said first surface of said first crystal at a first pair of spots,

a first reflective surface oriented to receive light beams from said first pair of spots of said second surface of said first crystal and to reflect such light beams,

a third surface adapted to receive such reflected light beams from said first reflective surface of said first crystal upon a second pair of spots, and

a fourth surface adapted to externally pass light beams impinged thereupon from said second pair of spots of said first crystal;

a second electro-optical crystal having

a first surface,

a second surface oriented to receive transmitted light from said second surface of said first crystal at a first pair of spots,

a first reflective surface oriented to receive light from said first pair of spots of said second surface of said second crystal and to reflect such received light,

a third surface adapted to receive such reflected light from said first reflective surface of said second crystal upon a second pair of spots, and

a fourth surface adapted to externally pass light beams impinged thereupon from said second pair of spots of said second crystal; a dielectric beam splitting coating;

said first crystal, said second crystal, and said coating being so oriented that

said first pair of spots of said second surface of said first crystal, and said first pair of spots of said second surface of said second crystal are substantially juxtaposed with a first portion of said coating oriented therebetween, and

said second pair of spots of said third surface of said first crystal, and said second pair of spots of said third surface of said second crystal are substantially juxtaposed with a second portion of said coating oriented therebetween;

means for varying the index of refraction of one of said crystals with respect to the index of refraction of the other of said crystals;

means associated with said fourth surface of said first crystal for reflecting one light beam from one spot of said second pair of spots of said first crystal;

a second polarization rotating means for rotating a first of said light beams from said fourth surface of said first crystal by ninety degrees so that the rotated first light beam and the unrotated second light beam are perpendicularly polarized with respect to each other;

a second polarization beam splitter, operated in reverse, coupled to receive the perpendicularly polarized output beams from said first crystal, and to provide a first single light beam which can be coupled to a first optical output means;

means associated with said fourth surface of said second crystal for reflecting one light beam from one spot of said second pair of spots of said second crystal;

a third polarization rotating means for rotating a first of said light beams from said fourth surface of said second crystal by ninety degrees so that the rotated first light beam and the unrotated second beam, from said second crystal, are perpendicularly polarized with respect to each other; and

a third polarization beam splitter, operated in reverse, coupled to receive the perpendicularly polarized output beams from said second crystal, and to provide a second single light beam which can be coupled to a second optical output means.

[*2] 2. Polarization-insensitive optical switching apparatus for switching a collimated input beam between two output means comprising

a first polarization beam splitter for receiving and splitting said collimated input beam into two perpendicularly polarized beams;

a first polarization rotating means for rotating a first of said two perpendicularly polarized beams by ninety degrees so that the rotated polarized beam and a second of said perpendicularly polarized beams are each polarized in the same direction;

means for reflecting one of said first and said second beams so that the reflected beam and the other of said first and said second beams traverse parallel paths;

polarization-sensitive interferometric multimode fiber optic switch means for receiving said reflected beam and said other beam at one input thereof, and for selectively providing said reflected beam and said other beam at a first pair of outputs and at a second pair of outputs;

means associated with said first pair of outputs for reflecting a beam selected from said reflected beam and said other beam;

a second polarization rotating means for rotating a first of said light beams from said first pair of outputs by ninety degrees so that the rotated first light beam and the unrotated second light beam are perpendicularly polarized with respect to each other;

a second polarization beam splitter, operated in reverse, coupled to receive the perpendicularly polarized output beams from said first pair of outputs, and to provide a first single light beam which can be coupled to a first optical output means;

means associated with said second pair of outputs for reflecting a beam selected from said reflected beam and said other beam;

a third polarization rotating means for rotating a first of said light beams from said second pair of outputs by ninety degrees so that the rotated first light beam from said second pair of outputs and the unrotated second light beam from said second pair of outputs are perpendicularly polarized with respect to each other; and

a third polarization beam splitter, operated in reverse, coupled to receive the perpendicularly polarized output beams from said second pair of outputs, and to provide a second single light beam which can be coupled to a second optical output means.

[*3] 3. The polarization-insensitive optical switching apparatus as recited in claim 2 wherein the index of refraction for one portion of said polarization-sensitive interferometric multimode fiber optic switch means is variable from the index of refraction for a second portion of said polarization-sensitive interferometric multimode fiber optic switch means.

[*4] 4. The polarization-insensitive optical switching apparatus as recited in claim 2 wherein said reflected one beam traverses a first path and a second path within a first portion and a second portion, respectively, of said polarization-sensitive interferometric multimode fiber optic switch means, wherein said other beam traverses a third path and a fourth path within a third portion and a fourth portion, respectively, of said polarization-sensitive interferometric multimode fiber optic switch means, wherein the index of refraction of said first portion is variable from said index of refraction of said second portion, and wherein the index of refraction of said third portion is variable from said index of refraction of said fourth portion.

Pat. No. 4474435 printed in FULL format.

4,474,435

<=2> GET 1st DRAWING SHEET OF 2

Oct. 2, 1984

Polarization-insensitive optical switch and multiplexing apparatus

INVENTOR: [Carlsen, John W.] Carlsen, W. John, Boston, Massachusetts
Melman, Paul, Newton, Massachusetts

ASSIGNEE-AT-ISSUE: GTE Laboratories Incorporated, Waltham, Massachusetts (02)

APPL-NO: 562,329

FILED: Dec. 16, 1983

CERTCORR: Corrections in Certificate of Correction dated Mar. 5, 1985 are entered herein.

REL-US-DATA:
Division of Ser. No. 327,873, Dec. 7, 1981

INT-CL: [3] G02F 1#03

US-CL: 350#381; 350#385; 350#388

CL: 350

SEARCH-FLD: 350#380-383, 388, 385

REF-CITED:

U.S. PATENT DOCUMENTS

3,499,701	3/1970	Macer et al.	350#380
3,632,187	1/1972	Kabegger	350#381
3,719,414	3/1973	Wentz	350#385

PRIM-EXMR: Arnold, Bruce Y.

LEGAL-REP: Fisher; Fred

CORE TERMS: crystal, polarized, polarization, spot, splitter, perpendicularly, path, rotating, oriented, optical, rotated, coating, input, ninety, coupled, refraction, reflective, splitting, switch, fiber, wave, electro-optical, collimated, traverse, beam, dielectric, electrodes, prism, polarization-insensitive, rotates

ABST:
Polarization-insensitive optical switch and dual channel carrier multiplexer includes a polarization beam splitter for receiving an input collimated beam which has arbitrarily polarized components, splitting the beam into the two components. One of the components is rotated by a 1/2 wave plate so as to yield a polarized beam which is polarized in the same direction as the other beam.

The two polarized beams are then applied to a polarization sensitive interferometric multimode fiber optic switch and modulator. The output of the interferometric multimode fiber optic switch and modulator contains two beams, both polarized in the same direction. One of the beams is rotated ninety degrees by a 1/2 wave plate, and the two mutually perpendicularly polarized beams are then recombined by a polarization beam splitter operated in reverse to yield an output beam containing mutually perpendicular components.

NO-OF-CLAIMS: 2

EXMPL-CLAIM: <=6> 1

NO-OF-FIGURES: 6

NO-DRWNG-PP: 2

PARCASE:

This is a division of application Ser. No. 327,873, filed Dec. 7, 1981.

SUM:

BACKGROUND OF THE INVENTION

1. Field of the Invention

This invention relates to polarization-insensitive optical switch apparatus, polarization-insensitive optical multiplexing apparatus, and interferometric multimode fiber optic apparatus in which the indices of refraction of various beam paths through portions thereof can be varied with respect to that of other portions. Accordingly, it is the general object of this invention to provide new and improved apparatus of such character.

2. Description of the Prior Art

Polarization-insensitive switching of multimode fibers has been achieved by means of mechanical switches which move an input fiber into alignment with two output fibers, at two stable positions.

Electronic carrier multiplexing of two optical signals has been accomplished. Usually, the multiplexing stage is performed electronically; the resulting signal modulates the current through a light source. The drive currents of two different light sources can be modulated, and the two signal carrying fibers can be combined into a single communication fiber by means of a fiber combiner.

Disadvantageously, mechanical switching is slow, is power consuming, is usually operated at high voltages, is cumbersome, and is unreliable.

Disadvantageously, the multiplexing techniques (in which a single light source is modulated by the already multiplexed signal) requires very high linearity of the modulated source in order to prevent crosstalk. The light sources used in communication systems have nonuniform, nonlinear responses, sufficient to make this method inapplicable in many cases.

The modulation of the drive currents of two different light sources, utilizing an optical combiner, disadvantageously has at least a 50%, or 3 dB, loss due to the principle of combination of two light beams. Typical losses described in the literature are approximately 4 dB.

SUMMARY OF THE INVENTION

It is another object of this invention to provide a new and improved polarization-insensitive optical fiber switch and dual channel carrier multiplexer.

Yet another object of this invention is to provide a new and improved optical switch apparatus in which operation is very fast compared to mechanical switching.

Still another object of this invention is to provide a new and improved low-loss device for optical switching and optical multiplexing which is polarization-insensitive.

Devices in accordance with this invention are of a low-loss nature due to the collimating optics and the large aperture of an interferometric multimode fiber optic switch and modulator, such as that described in our copending U.S. application Ser. No. 317,362, filed Nov. 4, 1981 and entitled "INTERFEROMETRIC MULTIMODE FIBER OPTIC SWITCH AND MODULATOR". Its polarization-insensitivity facilitates the apparatus for use with unpolarized light sources, such as LEDs. In a multiplexing configuration, the light source linearity problem and the combiner losses are eliminated. Its complementary output provides a second channel (or a monitoring signal) without the interruption of the light beam.

Still another object of this invention is to provide a new and improved polarization-insensitive electro-optical switch for use with multimode fibers.

Yet another object of this invention is to provide a new and improved modulator which can modulate two polarizations of an unpolarized light source with different signals.

Still yet another object of this invention is to provide a new and improved apparatus for multiplexing in which the 3 dB loss from the beam recombination process in a two signal multiplexing scheme can be eliminated.

Yet still another object of this invention is to provide for a polarization-insensitive fast multimode optical fiber switch or modulator, or a dual channel electronic carrier frequency multiplexer using a single light source and single fiber, in which, when operated in a switch mode, polarization losses inherent in electro-optical devices are eliminated, and when operated in a multiplexer mode, losses inherent in optical combiners due to basic optic restrictions are eliminated.

In accordance with one embodiment of the invention, a polarization-insensitive optical switch apparatus for switching a collimated input beam between two output means comprises a first polarization beam splitter for receiving and splitting the collimated input beam into two perpendicularly polarized beams. A first polarization rotating means rotates a first of the two perpendicularly polarized beams by ninety degrees so that the rotated beam and a second of the perpendicularly polarized beams are each polarized in the same direction. One of the first and the second beams is reflected so that the

reflected beam and the other of the first and second beams traverse parallel paths. A first electro-optical crystal has a first surface adapted to receive the reflected one beam and the other beam for transmission therethrough. The first crystal contains a second surface which is adapted to receive the transmitted beams from the first surface thereof at a first pair of spots. The crystal further contains a first reflective surface which is oriented to receive light beams from the first pair of spots and to reflect such light beams. The crystal further has a third surface which is adapted to receive the reflected light beams from the first reflective surface of the first crystal upon a second pair of spots. The crystal further contains a fourth surface which is adapted to externally pass light beams impinged thereupon from the second pair of spots. A second electro-optical crystal has a first surface. The second crystal further has a second surface which is oriented to receive transmitted light from the second surface of the first crystal at a first pair of spots. The second crystal further contains a first reflective surface which is oriented to receive light from the first pair of spots of the second surface of the second crystal and to reflect such received light. The second crystal further contains a third surface which is adapted to receive the reflected light from the first reflective surface of the second crystal upon a second pair of spots, the second crystal having a fourth surface which is adapted to externally pass light beams impinged thereupon from the second pair of spots of the second crystal. The embodiment further includes a dielectric beam splitting coating. The beam splitting coating and the two crystals are so oriented that the first pairs of spots of the two crystals are substantially juxtaposed with a first portion of the coating oriented therebetween. The second pairs of spots of the two crystals are substantially juxtaposed with a portion of the coating oriented therebetween. The index of refraction of one of the crystals can be varied with respect to that of the other. Means are associated with the fourth surface of the first crystal for reflecting one light beam from one spot of the second pair of spots thereof. A second polarization rotating means rotates a first of the light beams from the fourth surface of the first crystal by ninety degrees so that the rotated first light beam and the unrotated second light beam are mutually perpendicularly polarized. A second polarization beam splitter, which is operated in reverse, is coupled to receive the perpendicularly polarized output beams from the first crystal and to provide a first single light beam which can be coupled to a first optical output means. Means are associated with the fourth surface of the second crystal for reflecting one light beam from one spot of the second pair of spots thereof. A third polarization rotating means rotates a first of the light beams from the fourth surface of the second crystal by ninety degrees so that the rotated first light beam and the unrotated second beam, from the second crystal, are mutually perpendicularly polarized. A third polarization beam splitter, which is operated in reverse, is coupled to receive the perpendicularly polarized output beams from the second crystal, and to provide a second single light beam which can be coupled to a second optical output means.

In accordance with still another object of the invention, polarization-insensitive optical switch apparatus for switching a pair of collimated input beams between two output means includes a first polarization beam splitter for receiving and splitting one of the collimated input beams into two perpendicularly polarized beams. A first polarization rotating means rotates a first of the two perpendicularly polarized beams by ninety degrees so that the rotated polarized beam and a second of the perpendicularly polarized beams are each polarized in the same direction. One of the first and the second beams is reflected so that the reflected beam and the other of the first and the second beams traverse parallel paths. A first electro-optical crystal has a first

surface adapted to receive the reflected one beam and the other beam for transmission therethrough. The first crystal further has a second surface which is adapted to receive transmitted beams from the first surface at a first pair of spots. The first crystal has a first reflective surface which is oriented to receive light beams from the first pair of spots and to reflect such light beams, the first crystal further having a third surface adapted to receive the reflected light beams from the first reflective surface thereof upon a second pair of spots. The first crystal further has a fourth surface which is adapted to externally pass light beams impinged thereupon from the second pair of spots. The embodiment further includes second means associated with the fourth surface of the first crystal for reflecting one light beam from one spot of the second pair of spots. A second polarization rotating means rotates the first of the light beams from the fourth surface of the first crystal by ninety degrees so that the rotated first light beam and the unrotated second light beam are perpendicularly polarized with respect to each other. A second polarization beam splitter, which is operated in reverse, is coupled to receive the perpendicularly polarized output beams from the first crystal, and to provide a first single light beam which can be coupled to a first optical output means. A third polarization beam splitter receives and splits the other of the collimated input beams into two perpendicularly polarized beams. A third polarization rotating means rotates a first of the two perpendicularly polarized beams from the third polarization beam splitter by ninety degrees so that the rotated beam and a second of the perpendicularly polarized beams from the third polarization beam splitter are each polarized in the same direction. A third means reflects one of the first and the second beams from the third polarization rotating means so that the reflected beam and the other of the first and the second beams from the third polarization rotating means traverse parallel paths. A second electro-optical crystal has a first surface which is adapted to receive the one beam reflected by the third means and the other beam from the third polarization rotating means for transmission through the second crystal. The second crystal has a second surface which is adapted to receive the transmitted beams from the first surface of the second crystal at a third pair of spots, the second crystal having a first reflective surface which is oriented to receive light beams from the third pair of spots of the second surface thereof and to reflect such light beams. The second crystal further has a third surface adapted to receive such reflected light beams from the first reflective surface thereof upon a fourth pair of spots, and a fourth surface adapted to externally pass light beams impinged thereupon from the fourth pair of spots thereof. The embodiment further contains a dielectric beam splitting coating. The coating, the first crystal, and the second crystal are so oriented that the first pair of spots of the second surface of the first crystal, and the third pair of spots of the second crystal are substantially juxtaposed with a first portion of the coating oriented therebetween; a second pair of spots of the first crystal and a fourth pair of spots of the second crystal are substantially juxtaposed with a second portion of the coating oriented therebetween. Means are provided for varying the index of refraction of one of the crystals with respect to that of the other. Fourth means, associated with the fourth surface of the second crystal, reflect one light beam from one of the fourth pair of spots of the second crystal. A fourth polarization rotating means rotates a first of the light beams from the fourth surface of the second crystal by ninety degrees so that the rotated first light beam from the second crystal and the unrotated second light beam from the second crystal are mutually perpendicularly polarized. A fourth polarization beam splitter, which is operated in reverse, is coupled to receive the perpendicularly polarized output beams from the second crystal and to provide a second single output light beam which can be coupled to a second optical light

means.

In accordance still yet with another embodiment of the invention, polarization-insensitive optical multiplexing apparatus for independently modulating perpendicularly polarized components of a collimated input beam includes a first polarization beam splitter for receiving and splitting the input beam into two perpendicularly polarized beams. A first polarization rotating means rotates a first of the two perpendicularly polarized beams by ninety degrees so that the rotated polarized beam and a second of the perpendicularly polarized beams are each polarized in the same direction. Means are provided for reflecting one of the first and the second beams so that the reflected beam and the other of the first and the second beams traverse parallel paths. A first electro-optical crystal has a first surface which is adapted to receive the reflected one beam and the other beam for transmission therethrough. The first crystal has a second surface which is adapted to receive such transmitted beams from the first surface at a first pair of spots. The first crystal has a first reflective surface which is oriented to receive light beams from the first pair of spots and to reflect such light beams. The first crystal further has a third surface adapted to receive such reflected light beams from the first reflective surface of the first crystal upon a second pair of spots; the first crystal has a fourth surface adapted to externally pass light beams impinged thereupon from the second pair of spots of the first crystal. The embodiment further includes a second electro-optical crystal which has a first surface and which has a second surface oriented to receive transmitted light from the second surface of the first crystal at a first pair of spots. The second crystal has a first reflective surface oriented to receive light from the first pair of spots of the second surface thereof and to reflect such received light. The second crystal further contains a third surface which is adapted to receive such reflected light from the first reflective surface thereof upon a second pair of spots. The second crystal further has a fourth surface which is adapted to externally pass light beams impinged thereupon from the second pair of spots thereof. The embodiment further contains a dielectric beam splitting coating wherein the coating, the first crystal, and the second crystal are so oriented that the first pairs of spots of the second surfaces of the two crystals are substantially juxtaposed with the first portion of the coating oriented therebetween. Second pairs of spots of the third surfaces of the two crystals are substantially juxtaposed with a second portion of the coating oriented therebetween. One beam and the other beam traverse a first and a second path, respectively, within the first crystal. One beam and the other beam traverse a third path and a fourth path, respectively, within a second crystal. The index of refraction of the first path within the first crystal is varied with respect to that of the third path within the second crystal. Also, the index of refraction of the second path within the first crystal is varied with respect to that of the fourth path within the second crystal, the variation of the indices of refraction being independent of each other. Means, associated with the fourth surface of the first crystal, reflect one light beam from one spot of the second pair of spots thereof. A second polarization rotating means rotates a first of the light beams from the fourth surface of the first crystal by ninety degrees so that the rotated first light beam and the unrotated second light beam are perpendicularly polarized with respect to each other. A second polarization beam splitter, operated in reverse, is coupled to receive the perpendicularly polarized light beams from the first crystal and to provide a first single light beam which can be coupled to a first optical output means. In accordance with certain features of the invention, the foregoing embodiment can include, in association with the fourth surface of the second crystal, means

for reflecting one light beam from one spot of the second pair of spots of the second crystal. A third polarization rotating means rotates a first of the light beams from the fourth surface of the second crystal by ninety degrees so that the rotated first light beam and the unrotated second beam, from the second crystal, are mutually perpendicularly polarized. A third polarization beam splitter, operated in reverse, receives the perpendicularly polarized output beams from the second crystal and provides a second single light beam which can be coupled to a second optical output means.

In accordance with still yet another embodiment of the invention, a polarization-insensitive optical multiplexing apparatus for independently modulating perpendicularly polarized components of a pair of collimated input beams includes a first polarization beam splitter for receiving and splitting one of the input beams into two perpendicularly polarized beams. A first polarization rotating means rotates a first of the two perpendicularly polarized beams by ninety degrees so that the rotated polarized beam and a second of the perpendicularly polarized beams are each polarized in the same direction. A first means is provided for reflecting one of the first and the second beams so that the reflected beam and the other of the first and the second beam traverse parallel paths. A first electro-optical crystal has a first surface which is adapted to receive the reflected one beam and the other beam for transmission therethrough. The first crystal has a second surface which is adapted to receive the transmitted beams from the first surface thereof at a first pair of spots. The first crystal further has a first reflective surface which is oriented to receive light beams from the first pair of spots of the second surface thereof and to reflect such light beams. The first crystal further has a third surface which is adapted to receive the reflected light beams from the first reflective surface thereof upon a second pair of spots. The first crystal further has a fourth surface adapted to externally pass light beams impinged thereupon from the second pair of spots thereof. Thus, the one beam and the other beam traverse a first path and a second path, respectively, within the first crystal. Second means, associated with the fourth surface of the first crystal, reflect one light beam from one spot of the second pair of spots thereof. A second polarization rotating means rotates a first of the light beams from the fourth surface of the first crystal by ninety degrees so that the rotated first light beam and the unrotated second light beam are mutually perpendicularly polarized. A second polarization beam splitter, operated in reverse, is coupled to receive the perpendicularly polarized output beams from the first crystal and to receive a first single light beam which can be coupled to a first optical output means. A third polarization beam splitter receives and splits the other collimated input beam into two perpendicularly polarized beams. A third polarization rotating means rotates a first of the two perpendicularly polarized beams from the third polarization beam splitter by ninety degrees so that the rotated beam and a second of the perpendicularly polarized beams from the third polarization beam splitter are each polarized in the same direction. Third means reflects one of the first and the second beams from the third polarization rotating means so that the reflected beam and the other of the first and second beams from the third polarization rotating means traverse parallel paths. A second electro-optical crystal has a first surface which is adapted to receive one beam reflected by the third means and the other beam from the third polarization rotating means for transmission through the second crystal. The second crystal has a second surface adapted to receive such transmitted beams from the first surface thereof at a third pair of spots. The second crystal has a first reflective surface oriented to receive light beams from the third pair of spots of the second surface thereof and to reflect such light beams. The second

crystal has a third surface adapted to receive such reflected light beams from the first reflective surface thereof upon a fourth pair of spots; the second crystal has a fourth surface adapted to to externally pass light beams impinged thereupon from the fourth pair of spots thereof. Thus, one beam reflected by the third means and the other beam from the third polarization rotating means traverse a third path and a fourth path, respectively, within the second crystal. A dielectric beam splitting coating, the first crystal, and the second crystal are so oriented that the first pair of spots of the first crystal and the third pair of spots of the second crystal are substantially juxtaposed with a first portion of the coating oriented therebetween. The second pair of spots of the third surface of the first crystal and the fourth pair of spots of the second crystal are substantially juxtaposed with a second portion of the coating oriented therebetween. First means vary the index of refraction of the first path within the first crystal with respect to that of the third path within the second crystal. In similar fashion, second means vary the index of refraction of the second path within the first crystal with respect to that of the fourth path within the second crystal. Fourth means, associated with the fourth surface of the second crystal, reflects one light beam from one spot of the fourth pair of spots of the second crystal. A fourth polarization rotating means rotates a first of the light beams from the fourth surface of the second crystal by ninety degrees so that the rotated first light beam from the second crystal and the unrotated second light beam from the second crystal are perpendicularly polarized with respect to each other. A fourth polarization beam splitter, operated in reverse, is coupled to receive the perpendicularly polarized light beams from the second crystal and provides a second single output light beam which can be coupled to a second optical output means.

In accordance with still yet another embodiment of the invention, a combination includes a dielectric beam splitting coating which is affixed to portions of a first and a second electro-optical crystals with portions of crystals being juxtaposed. First means vary the index of refraction of one beam path through one of the crystals with respect to that of one beam path through the other. Second means vary the index of refraction of another beam path through one of the crystals with respect to that of another beam path through the other. The second means is independent from the first means. In accordance with certain features of the invention, the first means comprises a first set of electrodes deposited upon opposite portions of the crystals so as to encompass the one beam paths and the second means comprises a second set of electrodes deposited upon opposite portions of the crystals so as to encompass the other beam paths. The two sets of electrodes can be independent of each other.

In accordance with another embodiment of the invention, polarization-insensitive optical switching apparatus for switching a collimated input beam between two output conductors includes a first polarization beam splitter for receiving and splitting the input beam into two perpendicularly polarized beams. A first polarization rotating means rotates a first of the two perpendicularly polarized beams by ninety degrees so that the rotated polarized beam and a second of the perpendicularly polarized beams are each polarized in the same direction. Suitable means reflects one of the first and the second beams so that the reflected beam and the other of the first and the second beams traverse parallel paths. Polarization-sensitive interferometric multimode fiber optic switch means receives the reflected beam and the other beam at one input thereof, and selectively provides the reflected beam and the other beam at a first pair of outputs and at a second pair of outputs. Means associated with the first pair of outputs reflect a beam selected from the reflected beam and the

other beam. A second polarization rotating means rotates a first of the light beams from the first pair of outputs by ninety degrees so that the rotated first light beam and the unrotated second light beam are mutually perpendicularly polarized. A second polarization beam splitter, operated in reverse, receives the perpendicularly polarized output beams and provides a first single light beam which can be coupled to a first optical output means. Means associated with the second pair of outputs reflect a beam selected from the reflected beam and the other beam. A third polarization rotating means rotates a first of the light beams from the second pair of outputs by ninety degrees so that the rotated first light beam and the unrotated second light beam from the second pair of outputs are perpendicularly polarized with respect to each other. A third polarization beam splitter, operated in reverse, receives the perpendicularly polarized output beams from the second pair of outputs, and provides a second single light beam which can be coupled to a second optical output means. In accordance with certain features of the invention, the index of refraction for one portion of the polarization-sensitive interferometric multimode fiber optic switch means is variable from that of a second portion thereof. The reflected one beam can traverse a first path and a second path within a first portion and a second portion, respectively, of the polarization-sensitive interferometric multimode fiber optic switch means. The other beam can traverse a third path and a fourth path within a third portion and a fourth portion, respectively, of the polarization-sensitive interferometric multimode fiber optic switch means. The index of refraction of the first portion can be varied from that of the second portion. The index of refraction of the third portion can be varied from that of the fourth portion.

DRWDESC:
BRIEF DESCRIPTION OF THE DRAWING

Other objects and features of this invention, together with its construction and mode of operation, will become more apparent from the following description, when read in conjunction with the accompanying drawing, in which:

FIG. 1 is a schematic diagram of one embodiment of this invention;

FIG. 2 is a modular version of the embodiment shown in FIG. 1;

FIG. 3 is a "p" polarization version of the modulator embodiment depicted in FIG. 2;

FIG. 4 is a plan view of another embodiment of the invention utilizing an IMFOS, as described in greater detail hereinafter, the dotted lines illustrating an outline of electrodes applied to such IMFOS;

FIG. 5 is a plan view of still another embodiment of the invention, utilizing a modified IMFOS which uses rectangular shape crystals with individual electrodes being depicted in dotted line format; and

FIG. 6 is a cross-sectional view of the embodiment shown in FIG. 4, taken along the line 6-6 thereof.

DETDESC:

DESCRIPTION OF PREFERRED EMBODIMENTS

A polarization-insensitive optical switch and dual channel carrier multiplexer, in accordance with this invention, utilizes the interferometric multimode fiber optic switch (IMFOS) described in a copending patent application by the applicants hereof, entitled "Interferometric Multimode Fiber Optic Switch and Modulator" U.S. application Ser. No. 317,362, filed Nov. 4, 1981. Broadly, an IMFOS, as described in the above-identified application, includes a dielectric beam splitting coating affixed to portions of two electro-optical crystals with coated portions of the crystals being juxtaposed. The index of refraction of one of the crystals is varied with respect to that of the other.

The teachings of the copending application are incorporated herein by reference.

Referring to FIG. 1, an IMFOS 11 is represented schematically as a rectangle. The IMFOS 11 is similar to that described in the copending application in which a beam path is modulated in accordance with an electrical field applied thereto. By the application of particular fields, a light beam is switched on and off or is modulated at varying intensities. The IMFOS 11, as depicted in FIG. 1 is polarization sensitive, and light of one polarity only is normally handled therethrough, In the embodiment depicted in FIG. 1, light, which is s plane polarized, is conveniently handled.

A collimated input beam 12 either can be unpolarized or can contain arbitrarily polarized light beams therewithin. The input beam 12 is split into two perpendicularly polarized beams, a p beam and an s beam, by a polarization beam splitter 13. The polarization beam splitter 13 can be constructed of birefrigent prisms, such as, for example, Rochon prisms, or multilayer interference polarizers.

The p polarized beam passes through a 1/2 wave plate 14 which converts it into an s polarized beam. The s polarized beam, split by the polarization beam splitter 13, is reflected by a mirror 16 so that it, and the s polarized beam emitted from the 1/2 wave plate 14, traverse parallel paths and enter the IMFOS 11.

The two s polarized beams that enter the IMFOS 11 undergo an interference and intensity redistribution as described more fully in the above-identified pending application.

As depicted in FIG. 1, the s polarized beam (which exited from the 1/2 wave plate 14 through the IMFOS 11) is reflected by a mirror 17 to another polarization beam splitter 18 which is operated in reverse. The s polarized beam which had been reflected by the mirror 16 and past through the IMFOS 11, is rotated by a 1/2 wave plate 19 into a p polarized beam. The p polarized beam from the 1/2 wave plate 19 and the s polarized beam from the mirror 17 are recombined by the polarization beam splitter 18 (which operates in reverse) to provide an output signal or output beam 21 which contains mutually perpendicular polarized beams p and s.

A modulator version of the embodiment shown in FIG. 1, is depicted in FIG. 2. A collimated input beam 12 contains either mutually perpendicularly polarized beams p and s, or it can contain unpolarized light. The beam 12 is applied through a polarization beam splitter 13, as before, which reflects a portion of the beam to a prism 26 which reflects the s polarized portion thereof toward the IMFOS 11. That portion of the beam 12 which passes through the polarization

beam splitter 13 is emitted therefrom as a p polarized beam. The p polarized beam is rotated ninety degrees by the 1/2 wave plate 14. Thus, the prism 26 send an s polarized beam to the IMFOS and the 1/2 wave plate 14 sends an s polarized beam to the IMFOS 11. The s polarized beam from the 1/2 wave plate 14, which passes through the IMFOS 11, is reflected by another prism 37 to a polarization beam splitter 18 which is operated in reverse. The s polarized beam (which had been reflected by the prism 26) passes through the IMFOS 11 and is rotated ninety degrees by the 1/2 wave plate 19 into a p polarized beam. The p polarized beam passes through the polarization beam splitter 18 and the s polarized beam from the prism 37 is reflected by the polarization beam splitter 18 (which operates in reverse) so that the output 21 contains both the p and the s mutually perpendicular beams.

FIG. 3 depicts a p polarization version of that described in FIG. 2. A collimated input beam 12, as before, is either unpolarized or contains mutually perpendicularly polarized beams. The input beam 12 is applied to a polarization beam splitter 13, as before. A p polarization portion of the beam passes directly from the polarization beam splitter 13 to an IMFOS 11, passing therethrough. The s polarized beam, reflected by the polarization beam splitter 13, passes through a 1/2 wave plate 34 which converts the s polarized beam into a second p polarized beam which, in turn, is reflected by a prism 36. The p polarized beam, reflected by the prism 36, passes through the IMFOS 11 and, then passes through a polarization beam splitter 38, which operates in reverse. The p polarized beam from the polarization beam splitter 13, which passes through the IMFOS 11, is reflected by a prism 40, and passes through a 1/2 wave plate 39 to the polarization beam splitter 38 which operates in reverse. The p polarized beam from the prism 40 is rotated ninety degrees by the 1/2 wave plate 39 to yield an s polarized beam. The s polarized beam from the 1/2 wave plate 39 is reflected by the polarization beam splitter 38 which operates in reverse to yield an output beam 41 which contains both the p and the s mutually perpendicular polarized beams.

Referring to FIG. 4, there is depicted, in plane view, an IMFOS 101 which is of general shape as that depicted in our copending application. The IMFOS 101 includes a first electro-optical crystal 102 and a second electro-optical 103 which are separated by a dielectric beam splitting coating 104. The first crystal 102, the second crystal 103, and the coating 104 are so oriented with portions of them juxtaposed so that light paths from one crystal can pass through the dielectric beam splitting coating 104 into the other crystal.

Means are provided for varying the index of refraction of one of the crystals 102 with respect to that of the other crystal 103. Such means for varying the index of refraction can include electrodes 106, 107 formed on opposite sides of the crystal 103, and electrodes 108, 109 formed on opposite sides of the crystal 102. The electrodes 106, 107, 108, 109 can each be formed by depositing a layer 111 of chromium onto the respective crystals 102, 103 and, in turn, depositing individual layers of gold 112 onto the chromium layers 111. The chromium layers 111 adhere effectively to the electro-optical crystals 102, 103 and the gold layers 112 adhere effectively to the chromium layers 111. As depicted in FIG. 3, the crystallographic axes of the two crystals 102 and 103 are oriented in opposite directions. The voltages applied to the respective crystals are such that the polarities are alike in the same direction. As depicted in FIG. 6, it is positive at the top for both crystals and negative (with respect to the top) at the bottom of the two crystals. In lieu thereof, though not depicted in FIG. 6 but more fully described in the copending application, the two crystals can

be oriented with their crystallographic axes in the same direction but with the voltage polarities applied in opposite directions; that is, with the crystallographic axes both directed upward, one crystal can have a positive polarity at the top and negative at the bottom, while the other crystal can have a negative polarity at the top and a positive polarity at the bottom.

An unpolarized beam of light 12, applied to the device depicted in FIG. 4, is applied to a polarization beam splitter 13. A p polarized beam from the polarization beam splitter 13 continues therethrough and is rotated by 1/2 wave plate 14 to yield an s polarized beam 16. The polarization beam splitter 13 also directs an s polarized beam 117 away therefrom toward a prism 118 which reflects the s polarized beam 117 into the first electro-optical crystal 102. The s polarized beam 116, upon passing through the crystal 102, hits the dielectric beam splitter 104 at a first spot 121. The s polarized beam 117 hits the polarized beam splitter 104 at a second spot 122. The beam 116, upon hitting the spot 121, is split into two parts: 50% is reflected as a beam 216, while 50% passes through the beam splitter 104 as a beam 316 into the crystal 103. In similar fashion, the beam 117, upon hitting the spot 122 of the beam splitter 104, splits into two parts: 50% is reflected as a beam 217 while the remaining 50% passes through the beam splitter 104 as a beam 317, the beam 317 passing through the crystal 103. The beams 216, 217, which have been reflected by the beam splitter 104, remain within the crystal 102 and is reflected by one surface (a reflective surface) 123 thereof down onto a second pair of spots 126, 127, respectively, so that the beam 216 can pass through the dielectric beam splitter 104 as a beam 416 or can be reflected as a beam 516, the reflected beam 516 being within the crystal 102, the beam 216 being within the crystal 103. In similar fashion, the beam 217, which had been reflected by the surface 123, upon reaching the spot 127 of the beam splitter 104, passes therethrough as a beam 417 within the crystal 103 or is reflected by the beam splitter 104 as a beam 517 within the crystal 102.

The beam 416, which passes through the crystal 103, is reflected by a prism 131 to a polarization beam splitter 132 that is operated in reverse. The beam 417, an s polarized beam, exits from the crystal 103 and is rotated ninety degrees by a 1/2 wave plate 133 to a p polarized beam. The emitting p polarized beam enters the polarization beam splitter 132, which is operated in reverse so as to yield an output beam 134 which contains both p and s components.

In similar fashion, the beam 516, which exits from the crystal 102, is reflected by a prism 136 toward a polarization beam splitter 137 that is operated in reverse. The s polarized beam 517 from the crystal 102 is rotated ninety degrees by 1/2 wave plate 138 to yield a p polarized beam, which, in turn, passes through the polarization beam splitter 137. Since the polarization beam splitter 137 also emits the s polarized beam which had been reflected by the prism 136, the output beam 139 therefrom contains both p and s mutually perpendicularly polarized components of light.

As described in our copending application, referenced hereinabove, the phase velocity for a beam of light through one crystal can be changed with respect to that of another crystal by varying the index of refraction of one crystal with respect to the other. This is achieved by applying potentials of appropriate polarities acrqss the electro-optical crystals so as to cause the phase velocity for one beam path through one crystal to be different from that of a beam path through the other crystal. Hence, as depicted in FIG. 4, the entire crystal 102 can have its index of refraction varied independently of the entire crystal

103, and vice versa.

Referring to FIG. 5, there is depicted a device similar to that shown in FIG. 4 with several major changes. The device shown in FIG. 5 depicts a rectangular crystal version of an IMFOS including a first crystal 501 and a second crystal 502 adjacent to each other with a dielectric beam splitting coating 503 between their juxtaposed surfaces. A first collimated input beam 504 is applied as input A to the crystal 501. Optionally, a second input beam 506 can be applied to the crystal 502. Two possible outputs can be achieved: output A can be obtained as an output beam 507, output B can be obtained as an output beam 505.

The input collimated beams 504, 506 are unpolarized or, optionally, are beams which are mutually perpendicularly polarized. The input beams 504, 506 are applied to polarization beam splitters 507, 508, respectively. The beam splitter 507 permits a p polarized beam 510 to pass therethrough into the crystal 501. The polarization beam splitter 507 reflects a p polarized beam through a 1/2 wave plate 509 (changing it to an s polarized beam) to a prism 511 which reflects that s polarized beam 512 within the crystal 501.

In similar fashion, the optionally applied input beam 506 to the polarization beam splitter 508 passes through to the crystal 502 as an s polarized beam 513, a portion being reflected as a p polarized beam which enters a 1/2 wave plate 514 rotating it to an s polarized beam which is reflected by the prism 511 as an s polarized beam 516 which enters the crystal 502. The beams 510, 512 impinge upon the dielectric beam splitter 503 at spots 517, 518, respectively. The orientation of the components are such that beams 513, 516 impinge upon the spots 517, 518, respectively. The beams 510, 512, hitting the spots 517, 518, respectively, of the dielectric beam splitting coating 503, pass directly through (at a 50% reduction) the crystal 502 as beams 519, 521, respectively, and are reflected by the 50% beam splitter 503 (at a 50% reduction) as beams 522, 523, respectively, within the first crystal 501. Similarly, the beams 513, 516, impinging upon the spots 517, 518, pass directly through (at a 50% reduction) the dielectric beam splitting coating 503 as beams 522, 523, respectively, and are reflected (at 50% reduction) as beams 519, 521, respectively.

The beams 522, 523 are reflected at the surface 524 of the crystal 501 so that the beams 522, 523 impinge upon spots 526, 527 at the dielectric beam splitting coating 503. Likewise, the beams 519, 521, upon being reflected at the surface 528 of the crystal 502, also impinge upon the spots 526, 527 of the dielectric beam splitter 503. The reflected portions of the beams 523, 524 from the dielectric beam splitter 503, and the transmitted portions of the beams 519, 521 within the crystal 501, appear as beams 529, 531, respectively. In similar fashion, the transmitted components of the beams 522, 523 and the reflected components of the beams 519, 521 within the crystal 502, appear as beams 532, 533, respectively.

The s polarized beam 531 passes through the dielectric beam splitter 534 (which is operated in reverse) as an s component of the output beam 505. The s polarized beam 529 is reflected by a prism 536 to a 1/2 wave plate 537 which rotates it into a p polarized beam which is reflected by the polarization beam splitter 534 so that the output beam 508 also contains a p component.

In similar fashion, the s polarized beam 533 passes through a polarization beam splitter 538 (which is operated in reverse) as an s polarized beam

component of an output beam 507. The s polarized beam 532 is reflected by the prism 536 and is rotated by a 1/2 wave plate 539 to a p polarized beam to the polarization beam splitter 538 (which is operated in reverse) to reflect that p polarized beam as a component of the output beam 507. The output beam 507 contains both the p and s components.

The beam 522, as depicted in FIG. 5, traverses a path from the spot 517 (at the interface of the two crystals 501, 502) up to the top (as viewed in the drawing) surface 524 of the crystal 503 and down to the spot 526 at the interface of the two crystals 501, 502. Separately, it is noted that within the same crystal 501, there is a beam path 523 from the spot 518 at the interface of the two crystals 501, 502 to a top surface 504 and down to the spot 527 at the interface of the two crystals 501, 502. The paths 522, 523 are separate and distinct from each other and cross at one point as depicted in the drawing but do not interfere thereat. The index of refraction of the electro-optical crystal 501 can be varied in known fashion by varying the application of an electrical potential across the crystal. To change the index of refraction of each individual path, independent electrodes are placed across the different paths, as indicated in dotted outline. The electrodes are both at the top and the bottom of the crystal. The electrodes for the paths 522 include one set of electrodes 541A, 541B. The electrodes 541A, 541B are coupled to each electrically, but need not be performed at a surface of the crystal. In similar fashion, electrodes encompassing the path 523 can include electrodes 542A, 542B deposited at the top and bottom of the crystals encompassing the path 523. The electrodes 542A and B are coupled together.

Electrodes 542A, 543B encompass beam paths 519 from the spot 517 to the surface 528 and to the spot 526, respectively. Similarly, electrodes 544A, 544B encompass the beam path 521 from the spot 518 to the surface 528 and to the spot 527, respectively.

Thus, when the polarization-insensitive optical switch and dual channel carrier multiplexer, in accordance with this invention, is utilized as a switch, the phase retardation of both beams (that is, the entering p polarized beam and the entering s polarized beam) is identical and a single set of electrodes is used, as depicted generally in FIG. 4. When the invention is utilized as a multiplexer, each beam propagates between its own set of electrodes, as indicated in FIG. 5, and therefore can be modulated with different modulation signals. At each output port, as discussed hereinabove, there are two beams emitted, though not necessarily at the same time, and these two beams are combined utilizing a polarization beam splitter operated in reverse after one beam has past through a 1/2 wave plate. The output of the polarization beam splitter is a single light beam which can be coupled into a single fiber at each output port.

Various modifications can be performed without departing from the spirit and scope of this invention. For example, the two polarized beams, when modulated separately, need not be recombined into a single fiber. Two output focusing optics can direct each into separate output fibers.

CLAIMS: What is claimed is:

[*1] 1. Polarization-insensitive optical switch apparatus for switching a pair of collimated input beams between two output means comprising

a first polarization beam splitter for receiving and splitting one of said collimated input beams into two perpendicularly polarized beams;

a first polarization rotating means for rotating a first of said two perpendicularly polarized beams by ninety degrees so that the rotated polarized beam and a second of said perpendicularly polarized beams are each polarized in the same direction;

first means for reflecting one of said first and said second beams so that the reflected beam and the other of said first and said second beams traverse parallel paths;

a first electro-optical crystal having

a first surface adapted to receive said reflected one beam and said other beam for transmission through said first crystal,

a second surface adapted to receive such transmitted beams from said first surface of said first crystal at a first pair of spots,

a first reflective surface oriented to receive light beams from said first pair of spots of said second surface of said first crystal and to reflect such light beams,

a third surface adapted to receive such reflected light beams from said first reflective surface of said first crystal upon a second pair of spots, and

a fourth surface adapted to externally pass light beams impinged thereupon from said second pair of spots of said first crystal;

second means associated with said fourth surface of said first crystal for reflecting one light beam from one spot of said second pair of spots of said first crystal;

a second polarization rotating means for rotating a first of said light beams from said fourth surface of said first crystal by ninety degrees so that the rotated first light beam and the unrotated second light beam are perpendicularly polarized with respect to each other;

a second polarization beam splitter, operated in reverse, coupled to receive the perpendicularly polarized output beams from said first crystal, and to provide a first single light beam which can be coupled to a first optical output means;

a third polarization beam splitter for receiving and splitting the other of said collimated input beams into two perpendicularly polarized beams;

a third polarization rotating means for rotating a first of said two perpendicularly polarized beams from said third polarization beam splitter by ninety degrees so that the rotated beam and a second of said perpendicularly polarized beams from said third polarization beam splitter are each polarized in the same direction;

third means for reflecting one of said first and said second beams from said third polarization rotating means so that the reflected beam and the other of

said first and said second beams from said third polarization rotating means traverse parallel paths;

a second electro-optical crystal having

a first surface adapted to receive said one beam reflected by said third means and said other beam from said third polarization rotating means for transmission through said second crystal,

a second surface adapted to receive such transmitted beams from said first surface of said second crystal at a third pair of spots,

a first reflective surface oriented to receive light beams from said third pair of spots of said second surface of said second crystal and to reflect such light beams,

a third surface adapted to receive such reflected light beams from said first reflective surface of said second crystal upon a fourth pair of spots, and

a fourth surface adapted to externally pass light beams impinged thereupon from said fourth pair of spots of said second crystal;

a dielectric beam splitting coating; said first crystal, said second crystal, and said coating being so oriented that

said first pair of spots of said second surface of said first crystal, and said third pair of spots of said second crystal are substantially juxtaposed with a first portion of said coating oriented therebetween, and

said second pair of spots of said third surface of said first crystal, and said fourth pair of spots of said third surface of said second crystal are substantially juxtaposed with a second portion of said coating oriented therebetween;

means for varying the index of refraction of one of said crystals with respect to the index of refraction of the other of said crystals;

fourth means associated with said fourth surface of said second crystal for reflecting one light beam from one spot of said fourth pair of spots of said second crystal;

a fourth polarization rotating means for rotating a first of said light beams from said fourth surface of said second crystal by ninety degrees so that the rotated first light beam from said second crystal and the unrotated second light beam from the second crystal are perpendicularly polarized with respect to each other; and

a fourth polarization beam splitter, operated in reverse, coupled to receive the perpendicularly polarized output beams from said second crystal and to provide a second single output light beam which can be coupled to a second optical output means.

[*2] 2. Polarization-insensitive optical multiplexing apparatus for independently modulating perpendicularly polarized components of a pair of collimated input beams comprising

a first polarization beam splitter for receiving and splitting one of said collimated input beams into two perpendicularly polarized beams;

a first polarization rotating means for rotating a first of said two perpendicularly polarized beams by ninety degrees so that the rotated polarized beam and second of said perpendicularly polarized beams are each polarized in the same direction;

first means for reflecting one of said first and said second beams so that the reflected beam and the other of said first and said second beams traverse parallel paths;

a first electo-optical crystal having

a first surface adapted to receive said reflected one beam and said other beam for transmission through said first crystal,

a second surface adapted to receive such transmitted beams from said first surface of said first crystal at a first pair of spots,

a first reflective surface oriented to receive light beams from said first pair of spots of said second surface of said first crystal and to reflect such light beams,

a third surface adapted to receive such reflected light beams from said first reflective surface of said first crystal upon a second pair of spots, and

a fourth surface adapted to externally pass light beams impinged thereupon from said second pair of spots of said first crystal,

whereby said one beam and said other beam traverse a first path and a second path, respectively, within said first crystal;

second means associated with said fourth surface of said first crystal for reflecting one light beam from one spot of said second pair of spots of said first crystal;

a second polarization rotating means for rotating a first of said light beams from said fourth surface of said first crystal by ninety degrees so that the rotated first light beam and the unrotated second light beam are perpendicularly polarized with respect to each other;

a second polarization beam splitter, operated in reverse, coupled to receive the perpendicularly polarized output beams from said first crystal and to receive a first single light beam which can be coupled to a first optical output means;

a third polarization beam splitter for receiving and splitting the other of said collimated input beams into two perpendicularly polarized beams;

a third polarization rotating means for rotating a first of said two perpendicularly polarized beams from said third polarization beam splitter by ninety degrees so that the rotated beam and a second of said perpendicularly polarized beams from said third polarization beam splitter are each polarized in the same direction;

third means for reflecting one of said first and said second beams from said third polarization rotating means so that the reflected beam and the other of said first and said second beams from said third polarization rotating means traverse parallel paths;

a second electro-optical crystal having

a first surface adapted to receive one beam reflected by said third means and said other beam from said third polarization rotating means for transmission through said second crystal,

a second surface adapted to receive such transmitted beams from said first surface of said second crystal at a third pair of spots,

a first reflective surface oriented to receive light beams from said third pair of spots of said second surface of said second crystal and to reflect such light beams,

a third surface adapted to receive such reflected light beams from said first reflective surface of said second crystal upon a fourth pair of spots, and

a fourth surface adapted to externally pass light beams impinged thereupon from said fourth pair of spots of said second crystal,

whereby said one beam reflected by said third means and said other beam from said third polarization rotating means traverse a third path and a fourth path, respectively, within said second crystal; a dielectric beam splitting coating,

said first crystal, said second crystal, and said coating being so oriented that

said first pair of spots of said second surface of said first crystal, and said third pair of spots of said second crystal are substantially juxtaposed with a first portion of said coating oriented therebetween, and

said second pair of spots of said third surface of said first crystal, and said fourth pair of spots of said third surface of said second crystal are substantially juxtaposed with a second portion of said coating oriented therebetween;

first means for varying the index of refraction of said first path within said first crystal with respect to the index of refraction of said third path within said second crystal;

second means for varying the index of refraction of said second path within said first crystal with respect to the index of refraction of said fourth path within said second crystal;

fourth means associated with said fourth surface of said second crystal for reflecting one light beam from one spot of said fourth pair of spots of said second crystal;

a fourth polarization rotating means for rotating a first of said light beams from said fourth surface of said second crystal by ninety degrees so that the rotated first light beam from said second crystal and the unrotated second

light beam from the second crystal are perpendicularly polarized with respect to each other; and

a fourth polarization beam splitter, operated in reverse, coupled to receive the perpendicularly polarized output beams from said second crystal and to provide a second single output light beam which can be coupled to a second optical output means.

Pat. No. 5117239 printed in FULL format.

5,117,239

<=2> GET 1st DRAWING SHEET OF 2

May 26, 1992

Reversible time delay beamforming optical architecture for phased-array antennas

INVENTOR: Riza, Nabeel A., Clifton Park, New York

ASSIGNEE-AT-ISSUE: General Electric Company, Schenectady, New York (02)

ASSIGNEE-AFTER-ISSUE: Date Transaction Recorded: Jul. 13, 1994
ASSIGNMENT OF ASSIGNOR'S INTEREST (SEE DOCUMENT FOR DETAILS).
MARTIN MARIETTA CORPORATION 6801 ROCKLEDGE DRIVE BETHESDA,MD 20817
Reel & Frame Number: 7046/0736

Date Transaction Recorded: Jul. 14, 1997
ASSIGNMENT OF ASSIGNOR'S INTEREST (SEE DOCUMENT FOR DETAILS).
LOCKHEED MARTIN CORPORATION 6801 ROCKLEDGE DRIVE BETHESDA, MARYLAND 20817
Reel & Frame Number: 8628/0518

APPL-NO: 690,421

FILED: Apr. 24, 1991

INT-CL: [5] H01Q 3#22

US-CL: 342#375; 342#158

CL: 342

SEARCH-FLD: 342#375, 54, 157, 158

REF-CITED:

U.S. PATENT DOCUMENTS

4,929,956	5/1990	* Lee et al.	342#376

OTHER PUBLICATIONS

D. Dolfi, F. Michel-Gabriel, S. Bann, J. P. Huignard, "Two-Dimensional Optical Architecture for Time-Delay Beam Forming in a Phased-Array Antenna", vol. 16, Optics Letters, pp. 255-257 (Feb. 15, 1991).
D. Dolfi, J-P Buignard, M. Baril, "Optically Controlled True Time Delays for Phased Array Antenna", SPIE vol. 1102-Optical Technology for Microwave Applications IV (1989).
E. N. Toughlian, H. Zmuda, "A Photonic Variable FR Delay Line for Phased Array Antennas", IEEE Manuscript Report #0733-8724/90/1200 (1990).

PRIM-EXMR: Blum, Theodore M.

LEGAL-REP: Ingraham; Donald S.
Davis, Jr.; James C.
Snyder; Marvin

CORE TERMS: beam, array, optical, antenna, laser, coupled, phased, processing, polarization, electrical, optically, architecture, deflected, cascade, prism, orientation, diode, polarizing, splitter, control signals, photodiode, detector, phase, modulator, detected, input, display, pixel, antenna array, selectively

ABST:
A phased array antenna system has optical architecture comprising free space delay units and associated spatial light modulators compatible for operation with temporally incoherent or coherent laser light to produce signals having selected time delays to actuate antenna elements of an antenna array to transmit electromagnetic radiation at a selected beam angle from the phase array. The same optical architecture is used to process electromagnetic signals detected by the antenna array to produce an output signal for display or processing which corresponds to the radiation detected at the selected beam angle.

NO-OF-CLAIMS: 21

EXMPL-CLAIM: <=4> 1

NO-OF-FIGURES: 3

NO-DRWNG-PP: 2

SUM:

BACKGROUND OF THE INVENTION

This invention relates generally to signal processing systems and more particularly to beamforming controls for phased array antennas.

Phased array antenna systems employ a plurality of individual antennas or subarrays of antennas that are separately excited to cumulatively produce a transmitted electromagnetic wave that is highly directional. The radiated energy from each of the individual antenna elements or subarrays is of a different phase, respectively, so that an equiphase beam front, or the cumulative wave front of electromagnetic energy radiating from all of the antenna elements in the array, travels in a selected direction. The difference in phase or timing between the antenna activating signals determines the direction in which the cumulative beam from all of the individual antenna elements is transmitted. Analysis of the phases of return beams of electromagnetic energy detected by the individual antennas in the array similarly allows determination of the direction from which a return beam arrives.

Beamforming, or the adjustment of the relative phase of the actuating signals for the individual antennas (or subarrays of antennas), can be accomplished by electronically shifting the phases of the actuating signals or by introducing a time delay in the different actuating signals to sequentially excite the antenna elements to generate the desired direction of beam transmission from the

antenna.

Electronically shifting the phases of the actuating signals requires extensive equipment, including switching devices to route the electrical signals through appropriate hardwired circuits to achieve the desired phase changes. Electronic phase shifters are designed for use at a specific frequency and thus have significant drawbacks when employed in phased array antenna systems using broad band radiation. For example, most hardwired phase shifters are limited to frequency changes of 1% or less of the design frequency of the shifter in order to avoid beam squint, or the variation from the beam direction that would result with the same phase delay at the design frequency.

Optical control systems can be advantageously used to create selected time delays in actuating signals for phased array systems. Such optically generated time delays are not frequency dependent and thus can be readily applied to broadband phased array antenna systems. For example, optical signals can be processed to establish the selected time delays between individual signals to cause the desired sequential actuation of the transmitting antenna elements, and the optical signals can then be converted to electrical signals, such as by a photodiode array. Different types of optical architectures have been proposed to process optical signals to generate selected delays, such as routing the optical signals through optical fiber segments of different lengths; using deformable mirrors to physically change the distance light travels along a reflected path before being converted to an electrical signal; and utilizing free space propagation based delay lines, which architecture typically incorporates polarizing beam splitters and prisms.

The use of optical fiber segments to introduce delays requires the use of many optical switches and the splicing of numerous segments of fiber together. The costs of construction of such a device are substantial given the significant amount of design work and precision assembly work necessary to produce a device having the range and incremental steps of phase changes that are required in a typical system, such as for a phased array radar. The numerous switching and coupling elements also introduce very high optical losses in the beamforming circuitry, requiring significant optical power input. The structure of the circuitry makes it less compact and less rugged than other types of systems discussed below.

The deformable mirror system relies on the physical displacement of a mirror to effect the necessary time delay; an array of moveable mirrors allows the generation of a range of delayed optical signals. This type of system is less rugged and potentially prone to calibration errors given the requirement displacement of the mirror to achieve the small time delays required for the optical signals.

An optical architecture for a transmit-only control circuit utilizing coherent light in conjunction with free space delay units was proposed by D. Dolfi, F. Michel-Gabriel, S. Bann, and J. Huignard in the paper entitled "Two-dimensional optical architecture for time-delay beam forming in a phased-array antenna", Vol. 16, Optics Letters, pp. 255-57, Feb. 15, 1991. The system proposed by Dolfi utilizes a coherent beam of light from a laser which is directed through a cascade of free space delay devices comprising spatial light modulators, polarizing beam splitters and prisms. By selectively polarizing various light beams from the laser, the beams can be individually directed through one or more of the free space delay devices to introduce a time delay

to the beam. The delayed beams are ultimately directed through an array of microlenses to photodiodes which convert the optical signals into electrical signals to actuate the transmission antenna. Dolfi does not suggest the use of his device for processing signals from returned beams detected by the antenna. Additionally, the use of coherent light necessitates the use of high quality optical components in the system to maintain the coherence of the light from the laser source in order to modulate the laser beam by interference between two coherent beams. Given the sensitivity of such components to motion, this type of a system is less rugged than systems relying on incoherent light, which do not use the interference phenomenon.

It is accordingly a primary object of this invention to provide an optical beamforming architecture that can both process signals to control beams transmitted from a phased array antenna and process signals from return beams detected by a phased array antenna.

It is another object of the present invention to provide an optical beamforming architecture that has low optical losses, and that is compact and rugged.

It is a further object of this invention to provide an optical architecture that can be operated with either incoherent or coherent optical signals.

SUMMARY OF THE INVENTION

In accordance with the present invention, optical architecture for beamforming in a phased array antenna system both processes the signals to control the antenna beam in the transmit mode and processes the signals generated by returned beams detected by the antenna array. The phased array antenna system comprises an antenna array having multiple antenna elements, an optical signal processing system coupled to the antenna array, a modulated laser source, and a post processing detection and display system. In the transmit mode, a plurality of incoherent light beams from an intensity modulated laser source are directed into the optical signal processing system where the individual light beams are differentially time delayed and then are converted to electrical control signals to excite the individual antenna elements in the array. The differentially delayed optical signals produce corresponding differentially delayed electrical control signals for the antenna elements.

The optical signal processing system directs input optical beams through a plurality of free space delay devices which selectively delay the beams. Each light beam is directed through a pixel of a spatial light modulator (SLM), which rotates the polarization of the incident light beam by 0 degrees or 90 degrees, dependent on the control voltage applied to the pixel. The spatial light modulator is coupled to the free space delay device which comprises a polarizing beam splitter (PBS) and a prism. The light beam passes directly through the PBS or is deflected at a right angle to its original path, dependent upon its polarization. The light beams passed directly through the PBS continue on to the next spatial light modulator in the cascade of free space delay devices that comprise the signal processing system. The deflected light beam travels through the prism coupled to the PBS before being reflected back into the PBS and deflected back onto the same path that the light beam was on prior to being deflected into the prism. The size of the prism, and hence the distance the reflected beam travels in passing through it, determine the amount of time delay that is imparted to the deflected beam. Control of the pixel voltages in the respective SLMs in turn determines the polarization of each light beam at the

entrance to each free space delay device, thus allowing selection of the light beams that will have the polarization orientation that will result in the beam being deflected into the prism by the PBS and thereby delayed. At the end of the cascade of free space delay devices all of the now selectively delayed light beams, or optical control signals, are polarized along along a first direction before being directed to an output PBS that allows light of that polarization to pass to an array of photodiodes which convert the individual optical signals into correspondingly delayed electrical control signals. These electrical signals comprise the output energy of the signal processing system, which in turn is used to excite the individual antenna elements.

In the receive mode, the electrical signals generated by the antenna elements after detection of an incoming electromagnetic beam are directed to the signal processing system where they are converted to optical return signals by a laser diode array. The light beams are then switched into the circuit of free space delay mechanisms and pass through those devices, with the received signals from each antenna element following a selected path as described above with respect to the transmit mode. At the end of the cascade of the free space delay devices, the optical signals are polarized along a second direction before being directed to an output PBS which directs beams of that polarization to a photodiode detector assembly which adds the optical signals together and converts the combined optical signals to electrical signals for further processing or display. The same selection of delay sequences that determines the direction of a beam that is transmitted allows a particular direction to be viewed in the receive mode.

DRWDESC:

BRIEF DESCRIPTION OF THE DRAWING

FIG. 1 is a block diagram of a phased array antenna system comprising the present invention.

The FIG. 2 is a schematic representation of reversible time delay beamforming optical architecture and circuitry of the present invention.

FIG. 3 is a schematic representation of an optical adder for use with the present invention.

DETDESC:

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

In FIG. 1, a phased array antenna system 100 used as a radar or the like comprises an array control computer 105, an antenna array assembly 110, a laser assembly 130, an optical signal processing system 150, and a post-processing display and analysis system 200. Array control computer 105 is coupled to and generates signals to control and synchronize the operation, described below, of the components listed above so that antenna system 100 can operate in both a transmit and a receive mode with selected beamforming characteristics.

FIG. 2 illustrates in greater detail certain components of phased array antenna system 100. Electromagnetic energy is radiated by antenna array assembly 110 from a plurality of antenna elements 112 when the system operates in the transmit mode. As used herein, an antenna element may comprise one or more radiating devices (not shown) which, when excited by an electrical signal,

radiates electromagnetic energy into free space. In a phased array system, the antenna elements may be arranged in any geometric pattern that provides the desired beamforming and detection capabilities for the array. Antenna elements 112 are commonly arranged in rows and columns and the optimum number of elements varies based on the intended use of the array. For example, in a typical phased array radar system for target tracking, more than 1,000 antenna elements are used in the array.

Antenna elements 112 are coupled to signal processing system 150 via a transmit/receive switch 114. Switch 114 is controlled by array control computer 105 (FIG. 1), which generates a control command to change the condition of switch 114 between a transmit position and a receive position in coordination with other control signals for the optical signal processing system and the like. In the transmit mode, switch 114 couples antenna elements 112 to the output control signals from signal processing system 150, which signal drive antenna elements 112 to radiate electromagnetic energy into free space. In the receive mode, the switch couples the antenna elements to the signal processing system to direct signals generated by antenna elements 112 in response to detected electromagnetic energy incident on the antenna elements, i.e. return signals, into the signal processing system.

Signal processing system 150 comprises optical architecture 150a to generate the time delays in the drive signals for antenna elements 112. As used herein "optical architecture" refers to the combination of devices for manipulating the direction, polarization, and/or the phase or time delay of light beams. Laser assembly 130 generates the light beams to provide an input signal to the optical architecture of signal processing system 150 to create the drive signals for antenna elements 112 in the transmit mode.

A laser source 132 is advantageously a semiconductor laser, but may be any type of laser beam generator that can provide beam intensities sufficient for operation of the the optical signal processing system as described in this application. Laser source 132 is modulated by a microwave signal generator 134 and a modulator 136 to produce laser pulses of the desired frequency for use with the phased array antenna system. By way of example and not limitation, direct linear intensity modulation can be used which results in the intensity of the modulated light being linearly proportional to the amplitude of the driving microwave signal voltage and current. Modulator 136 may comprise a square root/bias circuit to produce the desired direct linear intensity modulation.

Laser source 132 is optically coupled to a spherical lens 138 in which the modulated laser output light beam is divided into a plurality of individual light beams. As used herein, "optically coupled" to refers to an arrangement in which one or more light beams are directed from one optical component to another in a manner to maintain the integrity of the signal communicated by the light beams. Lens 138 also acts as an optical collimator to cause light beams passing from it to travel in parallel paths. The individual light beams into which the output beam of laser source 132 is divided provide the control signals for driving the individual antenna elements 112; thus the total number of beams into which lens 138 must separate the output beam of laser source 132 is determined by the number of antenna elements 112 which are to be driven by optical signal processing system 150.

Although a coherent or a temporally incoherent output of laser assembly 130 may be used in accordance with this invention, the preferred embodiment of

this invention utilizes temporally incoherent light. As used herein, "temporally incoherent light" refers to laser light with a relatively broad spectrum, or poor coherence length. Thus, for the purposes of first describing the invention, it will be assumed that the optical output light beam of laser assembly 130 is temporally incoherent but polarized in a selected direction. For purposes of explanation, it will also be assumed that the output light beam of laser assembly 130 is polarized in the horizontal direction (p-polarized), although vertical (s-polarized) light can alternatively be used, so long as the particular polarization is selected for use in conjunction with the optical architecture as described below.

In accordance with the present invention, within the optical signal processing system 150 the plurality of light beams emerging from lens 138 are manipulated by the optical architecture to selectively time-delay individual light beams, and these individual light beams are converted into electrical signals having corresponding delays to drive antenna elements 112. Similarly, electrical signals generated by antenna elements 112 in the receive mode are converted to optical signals, manipulated by the same optical architecture, and reconverted to an electrical output signals which are directed to postprocessing display and analysis system 200 for operating a display or for further processing. For explanation purposes, the operation of the system in the transmit mode will be addressed first.

Laser assembly 130 is optically coupled to optical signal processing system 150. Temporally incoherent, polarized, and collimated light beams from laser assembly 130 enter processing system 150 at an input polarizing beam splitter (PBS) 152. PBS 152 allows light of a selected polarization to pass directly through the device, but light of an opposite polarization is deflected at a right angle to the incident angle of the light. For example, as illustrated in FIG. 2, input PBS 152 allows p-polarized light incident at side 152A from laser assembly 130 to pass directly through the device; oppositely (i.e. s-polarized) light incident at side 152B will be deflected 90 degrees.

Input PBS 152 is coupled to the first of a series, or cascade, of spatial light modulators (SLMs) 1541-154 n and associated free space delay devices 1561-156 n . SLM 1541 is a two-dimensional pixelated electrically addressed ferroelectric liquid crystal/polymer device typically having pixels arranged in columns and rows forming an array of A x B pixels. The pixels in this array are individually illuminated by light beams arranged in a corresponding A x B matrix, which light beams emerge from lens 138 and pass through input PBS 152. The SLM can alternatively be a nematic liquid crystal parallel rub device operated in the high speed transient nematic mode. Each pixel in SLM 1541 acts as a polarization rotator, rotating the polarization of the incident light beam by 0 or 90 degrees (e.g., if the pixel is selected to cause rotation of the polarization orientation of incident light, p-polarized light would be rotated to s-polarized light and vice versa). The selection of control voltages applied to the pixel determines the orientation of liquid crystals in the cell which in turn determines whether the polarization orientation of light passing through the cell will be rotated. The polarization of each of the incident light beams can be selectively adjusted by changing the control signals to the pixel array of an SLM. Such control signals are provided by array control computer 105.

SLM 1541 is optically coupled to an associated free space delay unit 1561. As used herein, an "associated free space delay device" refers to sequentially adjacent SLMs and free space delay units in the cascade of these devices, i.e.

SLM 1541 and free space delay unit 1561, SLM 1562 and free space delay unit 1562, etc. Each free space delay unit comprises a pair of polarizing beam splitters optically coupled to a prism, into which a light beam is deflected if it is to be time delayed in that free space delay unit. For example, light beams emerging from SLM 1541 are incident on delay unit 1561 and first enter a polarizing beam splitter (PBS) 158A1. Dependent on the polarization of the incident light beams, the beam either passes directly through PBS 158A1 into PBS 158B1 and continues in the same direction to the next SLM in the cascade, or it is deflected by 90 degrees in PBS 158A1. Light beams deflected 90 degrees enter a prism 1591 , in which the light beam traverses a path reflecting off walls of the prism before it is directed into PBS 158B1, in which the light is again deflected by 90 degrees to rejoin the path on which it was travelling at the time it entered free space delay device 1561. As a deflected beam will have travelled a greater distance in passing through the prism as compared to a companion beam that was not deflected by PBS 1581,it will have a slight time delay with respect to the undeflected beam.

SLM 1542 is optically coupled to free space delay unit 1561 so that light beams passing out of free space delay unit 1561 will illuminate the A x B pixelated array of SLM 1542. The polarization orientation of each light beam can again be selected by controlling the pixels to either rotate or not rotate the light beam. SLM 1542 is optically coupled to associated free space delay unit 1562, which comprises PBS pair 158A2 and 158B2 and prism 159(2). Free space delay unit 1562 acts on the plurality of p- and s-polarized light beams in a manner similar to that described above with respect to free space delay unit 1561, with the light beams being passed either directly through or deflected into prism 1592, dependent on the polarization of the individual beam. Prism 1592 typically provides a longer path for the light to traverse, thereby creating a longer delay time than would prism 1591 with respect to an underflected beam. Similarly, each subsequent free space delay unit in the cascade would create a longer time delay in a deflected light beam.

The cascade of associated SLMs and free space delay units, up to "n" such associated groups, affords the opportunity to produce 2<n > different delay values for light beams passing through optical signal processing system. Time delays for individual beams are determined by the number of free space delay units in which the beam is deflected through the prism and the length of the path that the light beam travels through each of the prisms (determined, for example, by the physical size of the prism).

The last free space delay unit 156 n in the cascade is optically coupled to an optical adder 160 which produces output light beams, with each of the light beams having the same polarization. An output SLM 161, which is capable of selectively rotating the polarization orientation of individual light beams passing through its A x B pixelated display, is advantageously used for this purpose. As the polarization orientation of each of the light beams at the output of free space delay unit 156 n is determinable based upon the orientation shifts made as the beams passed through the cascade of SLMs and associated free space delay devices, the pixel control voltages are adjusted on output SLM 161 to rotate light beams to a selected polarization orientation, such as p-polarity. Light beams already having the selected polarization orientation pass through output SLM 161 unrotated; thus all light beams emerging from SLM 161 have the selected polarization orientation.

Optical adder 160 may alternatively comprise a polarization rotation unit 162, as illustrated in FIG. 3. Components of rotation unit 162 include a 45-degree oriented polarizer 164, which effectively combines both p- and s-polarized beams, albeit at the reduced intensities seen at 45 degrees relative to the polarization axes of the respective beams. A half wave plate 166 is optically coupled to 45 degree polarizer 164 to receive light emerging therefrom. Half wave plate 166 shifts the 45 degree oriented uniform polarization to a selected polarization orientation, for example p-polarized orientation. A liquid crystal cell 168 is optically coupled to half wave plate 166 and, dependent upon the applied voltage, allows light to pass through with its polarization orientation unchanged or selectively rotates the p-polarized light exiting half wave plate 166 to s-polarized light.

An output polarizing beam splitter 170 is optically coupled to a focusing lenslet array 175 and to a detector assembly 190. Dependent upon the polarization of the incident light, output PBS 170 causes the light beams to be directed to a photodiode array 180 via lenslet array 175, or to detector assembly 190. For example, in the transmit mode, each of the plurality of light beams emerging from uniform polarization unit 160 is p-polarized and will pass through output PBS 170 to be coupled with photodiode array 180.

Photodiode array 180 comprises an array of A x B photodiodes corresponding to the plurality of light beams emerging from output PBS 170. The optical control signals, or light beams, incident on array 180 are converted to electrical signals. The electrical signals generated by photodiode array 180 are delayed by time intervals corresponding to the time delays imparted to the optical control signals; these electrical signals are connected through transmit/receive switch 114 to antenna elements 112, which, when excited by the electrical signals, radiate electromagnetic radiation into free space in the desired direction.

In accordance with the present invention, optical signal processing system 150 processes both signals for use in the transmit mode and signals for use in the receive mode. The optical architecture described above, from input PBS 152 to output PBS 170, operates in the same fashion in the receive mode as described above with respect to the transmit mode. Signal processing system 150 comprises a laser diode array 185 and a detector assembly 190 which are used in the receive mode as described below.

Laser diode array 185 is electrically coupled to transmit/receive switch 114 and optically coupled to input PBS 152 via a collimating lenslet array 187. Laser diode array 185 comprises a plurality of laser diodes arranged in an A x B array corresponding to the array pattern used in the optical architecture for processing the transmit signals. The laser diodes may be of any type that are capable of producing a laser light pulse of an intensity and frequency compatible with the optical architecture, in response to the electrical signals received from transmit/receive switch 114. In operation, electrical return signals generated by antenna elements 112 in response to detected electromagnetic radiation are electrically conducted to laser diode array 185 which converts the electrical signals into corresponding optical return signals. The polarization orientation of light beams generated by laser diode array 185 is selected to result in light of that polarization being deflected, upon reaching input PBS 152, into the cascade of SLMs 154 and free space delay units 156. The paths followed by individual light beams passing through the cascade is selected as described above with respect to the optical signals processed in the transmit mode.

Output PBS 170 is optically coupled to photodiode detector assembly 190, which comprises a combining lens 192 and an optical detector 194. Combining lens 192 focuses the plurality of light beams onto detector 194 which converts the combined optical return signals into an electrical return signal, the strength of which depends on the instantaneous relative time delays between the different beams incident on detector 194 and the instantaneous intensity of the combined light beams on detector 194. Detector 194 is electrically coupled to post-processing display and analysis system 200 for producing a display or for further processing of the signal information. When optical signal processing system 150 is operating in the receive mode, as directed by array control computer 105, uniform polarization unit 160 selectively rotates each of the light beams to have, for example, an s-polarization, in which case the light is deflected by output PBS 170 to detector assembly 190.

In the receive mode, phased array antenna system 100 is used to "view" a particular angle of space with respect to the antenna array to determine the intensity of electromagnetic radiation of the desired frequency being received from that direction. In a radar system, for example, the strength or intensity of the radiation received from a given angle determines whether a target is detected in that direction. The time delays set in the cascade of free space delay units and associated SLMs determine the beam angle of the phased array antenna in either a transmit or a receive mode. Thus, in the receive mode, only the sum of the signals detected by the antenna array from a selected direction is necessary to determine the presence of reflected electromagnetic radiation from that beam angle.

Operation of the optical signal processing system may alternatively be accomplished through interference and heterodyne detection using coherent laser light. Such operation would necessitate using the appropriate equipment (not shown) in laser assemblies 130 and 180 to create two mutually coherent laser beams. This arrangement would require, for both transmit and receive operations, that the phase of the output light beam of laser assembly 130 be locked with that of the output beams of laser diode array 180. The locking can be accomplished through known frequency injection mode locking techniques used for temporally locking laser diodes. In the transmit mode, amplitude modulated laser 132 provides the signal beam, while laser diode array 185 operating in the continuous wave (CW) mode provides the reference beam for interference. In the receive mode, laser 132 operating in the CW mode provides the reference beam, while laser diode array 185, amplitude modulated by the received electrical signals from antenna array 112, forms the signal beam. The output beams from both laser 132 and laser diode array 185 are polarized in the same direction, for example p-polarized, and PBS 152 is replaced by a non-polarizing cube beam splitter (BS) (not shown). In this arrangement, half of the light from laser 132 and laser diode array 185 is directed toward SLM 1541, while half of the light is directed out of the BS to provide the mode-locking signals.

It will be readily understood by those skilled in the art that the present invention is not limited to the specific embodiments described and illustrate herein. Many variations, modifications and equivalent arrangements will now be apparent to those skilled in the art, or will be reasonably suggested by the foregoing specification and drawings, without departing from the substance or scope of the invention. Accordingly, it is intended that the invention be limited only by the spirit and scope of the appended claims.

CLAIMS: What is claimed is:

[*1] 1. A phased array antenna system comprising:

a plurality of antenna elements arranged in an array, said array being operable in a transmit or a receive mode;

an optical signal processing system coupled to said array, said system generating differentially time-delayed optical control signals to control output beam radiation patterns transmitted from said array and to optically process return radiation patterns detected by said array; and

a modulated laser source optically coupled to said signal processing system and having means for dividing light from said laser source into a plurality of collinear light beams;

said optical signal processing system comprising:

a plurality of spatial light modulators optically coupled to associated free space delay units so as to selectively time delay each of said plurality of light beams,

means for converting said optical control signals into corresponding electrical signals to excite said antenna elements in said transmit mode,

means for converting electrical signals produced by said antenna elements in response to detected electromagnetic radiation in said receive mode into corresponding return optical signals, and

means for converting said return optical signals after said optical processing into electrical signals.

[*2] 2. The phased array antenna system of claim 1 wherein said means for dividing light from said laser source into a plurality of beams comprises a collimating lens.

[*3] 3. The phased array antenna system of claim 1, wherein each of said free space delay units further comprises a pair of polarizing beam splitters optically coupled to a prism to provide a selected time delay to at least one of said plurality of light beams.

[*4] 4. The phased array antenna system of claim 1 further comprising an optical adder to uniformly polarize each of said light beams emerging from said pluralilty of spatial light modulators and free space units.

[*5] 5. The phased array antenna system of claim 4 wherein said optical adder comprises a spatial light modulator.

[*6] 6. The phased array antenna system of claim 4 wherein said optical adder comprises a 45 degree oriented polarizer optically coupled to a half-wave plate.

[*7] 7. The phased array antenna system of claim 6 further comprising a liquid crystal cell optically coupled to said half wave plate, said cell being coupled to selectively rotate the polarization orientation of incident light

beams.

[*8] 8. The phased array antenna system of claim 4 further comprising an input polarizing beam splitter to direct incident light of selected polarization orientations into said time delaying means.

[*9] 9. The phased array antenna system of claim 4 further comprising an output polarizing beam splitter (PBS) optically coupled to receive light from said optical adder and optically coupled to transmit light of a first selected polarization orientation to said means for converting optical signals into corresponding electrical signals to excite said antenna elements and to transmit light of a second selected polarization rotation to said means for converting the processed optical return signals into electrical signals.

[*10] 10. The phased array antenna system of claim 9 wherein said means for converting the processed return optical signals to electrical signals comprises a photodiode detector assembly.

[*11] 11. The phased array antenna system of claim 10 wherein said photodiode detector assembly is optically coupled to said output polarizing beam splitter.

[*12] 12. The phased array antenna system of claim 1 wherein said means for converting said optical control signals into corresponding electrical signals to excite said antenna elements comprises an array of photodiodes.

[*13] 13. The phased array antenna system of claim 1 wherein said means for converting electrical signals generated by said array in said receive mode into corresponding return optical signals comprises an array of laser diodes.

[*14] 14. The phased array antenna system of claim 1 wherein said light beams are comprised of temporally incoherent laser light.

[*15] 15. The phased array antenna system of claim 1 wherein said light beams are comprised of coherent laser light.

[*16] 16. The phased array antenna system of claim 1 wherein said modulated laser source comprises a semiconductor laser and means electrically coupled to said laser for direct linear modulation of said laser.

[*17] 17. The phased array antenna system of claim 1 further comprising a transmit/receive switch to selectively electrically couple said antenna array to said means for converting optical control signals into corresponding electrical signals and to said means for converting electrical signals to corresponding optical return signals.

[*18] 18. The phased array antenna system of claim 1 further comprising an array control computer coupled to said optical control system, said laser source, and said antenna array to control operation of said phased array antenna system in said transmit and said receive modes.

[*19] 19. A phased array radar system comprising:

an array control computer,

an antenna array having a plurality of elements, said array being operable in a transmit or receive mode,

a post detection display and analysis system,

a modulated laser source, and

an optical signal processing system electrically coupled to said antenna array and said post detection display and analysis system and optically coupled to said laser source,

said array control computer being coupled to said antenna array, said post detection display and analysis system, said modulated laser source and said optical signal processing system to control the combined operation thereof in said transmit and receive modes,

said signal processing system comprising:

an optical architecture having an input polarizing beam splitter, a cascade of spatial light modulators and associated free space delay units to delay signals passing therethrough, said cascade being optically coupled to receive light beams from said input polarizing beam splitter, an optical adder optically coupled to said cascade to uniformly polarize light passing from said cascade, and an output polarizing beam splitter optically coupled to said adder,

an array of photodiodes to convert time delayed optical signals passing from said optical architecture into corresponding electrical signals,

an array of laser diodes to convert electrical signals generated by said antenna array in response to detected electromagnetic radiation into corresponding optical signals for application to said optical architecture, and

a detector assembly optically coupled to said optical architecture to convert said optical signals into an electrical output.

[*20] 20. The phased array radar system of claim 19 wherein each of said spatial light modulators and associated free space delay units in said cascade produce a time delay of different duration.

[*21] 21. The phased array radar system of claim 20 wherein said laser source produces temporally incoherent light.

Pat. No. 5319477 printed in FULL format.

5,319,477

<=2> GET 1st DRAWING SHEET OF 5

Jun. 7, 1994

Compact polarization independent optical switching units

INVENTOR: DeJule, Michael C., Clifton Park, New York
Credelle, Thomas L., Los Gatos, California
Riza, Nabeel A., Clifton Park, New York
Castleberry, Donald E., Schenectady, New York

ASSIGNEE-AT-ISSUE: General Electric Company, Schenectady, New York (02)

APPL-NO: 994,011

FILED: Dec. 21, 1992

INT-CL: [5] G02F 1#133.5; H01Q 3#34

US-CL: 349#65; 342#375; 359#140;

CL: 349;342;359;

SEARCH-FLD: 359#42, 41, 140, 251, 7; 342#374, 375

REF-CITED:

U.S. PATENT DOCUMENTS

4,478,494	10/1984	* Soref	359#42
4,836,658	6/1989	* Laycock	359#7
5,117,239	5/1992	* Riza	342#375
5,231,405	7/1993	* Riza	342#375

OTHER PUBLICATIONS

Wagner & Cheng, "Electrically Controlled Optical Switch for Multimode Fiber Applications", Applied Optics, Sep. 1, 1980, vol. 19, No. 17, pp. 2921-2925.

PRIM-EXMR: Sikes, William L.

ASST-EXMR: Mai, Huy

LEGAL-REP: Snyder; Marvin

CORE TERMS: optical, switching, beam, path, switch, coupled, input, polarization, cascade, passing, pixel, processing, sequentially, optically, deflected, array, rotation, beamsplitter, plane, prism, fiber, orthogonal, constituent, mirror, axes, splitter, sequential, electrical, polarizing, recombined

ABST:

A compact optical switching unit includes a polarization independent

beamsplitter switch (PIBS) coupled to a delay path apparatus such that incident light beams are respectively selectively directed along either a direct path or a delay path dependent on the the manipulation of the polarization of polarized constituent light beams in the PIBS. The delay path apparatus is typically a mirror prism or fiber optic cable disposed such that light deflected onto the delay path traverses a longer distance than light passing along the direct path and thus a particular light beam can be selectively time delayed by controlling the PIBS to direct the beam into desired delay paths in a cascade of optical signal switching units. A compact and readily fabricated cascade of optical switching units includes PIBS blocks, a portion of which constitutes the PIBS in respective optical switching units sequentially optically coupled. Delay path apparatuses disposed along an axis orthogonal to both the axis of beams passing along a direct path through polarizing beam splitter switches on the direct path and the axis between respective optical switching units result in a compact optical architecture.

NO-OF-CLAIMS: 20

EXMPL-CLAIM: <=7> 1

NO-OF-FIGURES: 9

NO-DRWNG-PP: 5

SUM:

RELATED APPLICATIONS AND PATENTS

This application is related to the application entitled "Compact Polarization Dependent Optical Switching Units", Ser. No. 07/994,012 (RD-21,313), filed concurrently with this application and assigned to the assignee of the present application, and which is incorporated herein by reference.

BACKGROUND OF THE INVENTION

Optical signal processing systems are used to manipulate the characteristics of optical signals, or light beams, to enable information or signals to be processed. For example, the direction, intensity, polarization, phase, or a combination of these characteristics of a light beam may be manipulated by appropriate equipment so that the manipulated characteristics impart the desired processing of the optical signal. For example, optical signal processing systems can be advantageously used for controlling phased array radars. In such a system, differentially time-delayed optical signals can be generated to establish selected time delays between individual optical signal beams, and the optical signals can then be converted to electrical signals to drive the antenna array with the desired sequential actuation of the transmitting antenna elements.

An essential component in most optical processing systems, such as phased array antenna controllers, is an efficient light switch. A key characteristic of a light switch used in a signal processing system, in which the processed light must commonly pass through many switches, is the amount of optical loss or attenuation that the light beam experiences in passing through the switch. A commonly used light switch is a lithium niobate based switch that provides

relatively fast switching times but typically also has about 3 dB light loss per switch. Thus, for example, if an optical signal passed through only seven switches in a signal processing system, it would lose 21 dB, that is the light amplitude of the output signal drops to 1/128th of the input amplitude.

One efficient, low loss, light switch includes a beam splitter and a liquid crystal array to selectively control the polarization of light beams entering the beams splitter. One example of switching using polarizing beam splitters (PBS) and liquid crystal arrays to selectively control the polarization of light entering the PBSs is disclosed in U.S. Pat. No. 5,117,239 of N. Riza, issued May 26 1992 and which is assigned to the assignee of the present application and incorporated herein by reference. For example, separate spatial light modulators (SLMs) comprising arrays of liquid crystals can be paired with sets of paired polarizing beam splitters in optical time delay units such that light passing through the unit passes along either a direct path or a delay path dependent on the polarization of the light.

Additionally, polarization-independent types of beamsplitter switches have been suggested that enable a non-polarized light beam to be selectively directed along a predetermined path. One example of such a polarization-independent switch is described by Wagner and Cheng in "Electrically Controlled Optical Switch For Multimode Fiber Applications," Applied Optics, Vol. 19, No. 17, September 1980, pp 2921-2925. In optical signal processing systems, use of polarization independent switches can be advantageous as the there is no reduction in light beam intensity (as may occur if a polarizer is used to polarize light to be used in a polarization-dependent system) and connections between modules of the signal processing system can be made with optical fibers that do not require polarization-maintaining fibers.

It is desirable that switching units in optical signal systems have relatively low attenuation, be of compact size, rugged, readily fabricated and adapted to processing a large number of separate signal light beams as would be necessary for operation of a phased array antenna system. It is further desirable, from the standpoint of manufacturing ease and efficiency, that each optical switch comprise as few optical devices, such as beamsplitters, as practicable. Additionally, it is desirable to have a switching unit that can readily be fabricated to produce a small time delay.

It is accordingly an object of this invention to provide a polarization independent optical switching unit having relatively low light attenuation and that is readily adapted to use in a cascade of other optical processing devices.

It is a further object of this invention to provide a polarization independent optical switching unit that is compact and rugged and that can be readily fabricated in a cascade of similar devices.

It is a still further object of this invention to provide an arrangement for a polarization independent optical switching unit that is readily adapted to generating small time delays between respective optical signal beams.

SUMMARY OF THE INVENTION

In accordance with this invention an optical signal control system is provided which includes at least one optical switching unit having a polarization independent beamsplitter switch (PIBS) coupled to a delay path apparatus such that light incident on the optical switching unit passes

through it either along a direct path or along a delay path dependent on which of two input axes the light enters the PIBS and on the polarization rotation applied to the light beams passing through PIBS. Each PIBS includes an input switch unit coupled to a spatial light modulator (SLM) that is in turn coupled to an output switch unit. Each delay path apparatus, such as an optical fiber strand or a corner prism/mirror arrangement, is coupled to receive light from an output switch unit of a corresponding optical switching unit PBS and to direct the light along a delay path to an input switch unit of an optical switching unit. Each SLM typically comprises an array of independently controllable liquid crystal pixels.

A plurality of optical switching units are typically sequentially coupled together in cascade. In one embodiment of this invention, a delay path apparatus is coupled between the output switch unit of a PIBS in one optical switching unit and the input switch unit of the PIBS in the next sequential optical switching unit; in an alternative embodiment, a delay path apparatus is coupled to receive light from the output switch unit of the PIBS in one optical switching unit and to direct the light along the delay path into the input switch unit of the same optical switching unit. In another embodiment, at least a portion of the optical switching units coupled together in cascade are disposed along a first axis and each of the input switch units and output switch units in sequentially coupled optical switching units comprise adjoining contiguous portions of respective input and output switch blocks. Similarly, respective SLMs in PIBSs in sequentially coupled optical switching units may comprise adjoining contiguous portions of a polarization rotation switch block.

In a cascade of optical switching units disposed along a first axis, respective time delay apparatuses in one embodiment are "folded", that is, disposed along respective axes not aligned with the first axis such that light passing along direct and delay paths in the cascade is deflected in all three dimensions. In a further embodiment, the delay path apparatuses are aligned along a second axis that is orthogonal but coplanar with the first axis; in an alternative embodiment, the first and second axes are disposed in respective mutually orthogonal planes.

DRWDESC:
BRIEF DESCRIPTION OF THE DRAWINGS

The features of the invention believed to be novel are set forth with particularity in the appended claims. The invention itself, however, both as to organization and method of operation, together with further objects and advantages thereof, may best be understood by reference to the following description in conjunction with the accompanying drawings in which like characters represent like parts throughout the drawings, and in which:

FIG. 1 is a schematic diagram of one embodiment of a portion of an optical signal processing system comprising the present invention.

FIGS. 2(A) through 2(D) are schematic diagrams of a polarization independent beamsplitter switch in accordance with the prior art.

FIG. 3 is a schematic diagram of a portion of a second embodiment of an optical signal processing system comprising the present invention.

FIG. 4(A) is a schematic diagram of a portion of a third embodiment of an optical signal processing system comprising the present invention.

FIG. 4(B) is a cross-sectional view of a portion of the third embodiment of an optical signal processing system comprising the present invention taken along the line 1-1 in FIG. 4(A).

FIG. 5 is a schematic diagram of a portion of a fourth embodiment of an optical signal processing system comprising the present invention.

DETDESC:

DETAILED DESCRIPTION OF THE INVENTION

FIG. 1 illustrates a portion of an optical signal processing system 100 as used in a phased array radar or the like and which comprises a light source 105, a plurality of optical switching units 1101-110 n optically coupled in a cascade arrangement, and an optical/electrical signal conversion circuit 200. As used herein, "cascade arrangement" refers to two or more components optically coupled such that light beams can pass sequentially from one component to the next component to which it is coupled.

Optical signal processing system 100 typically is used to generate a number of differentially time delayed optical signals (or light beams) that, when converted to corresponding electrical signals, drive respective elements in an antenna array (not shown). Light source 105 typically comprises a laser adapted to provide light beams of the appropriate intensity required for use in the processing system. Light source 105 typically further comprises one or more collimating lenses (not shown) disposed to receive light from the laser and to collimate the light into a plurality of collinear light beams which pass into first optical switching unit 1101. Optical/electrical conversion circuit 200 typically comprises photodetectors and associated electrical components, such as amplifiers, mixers, and filters (not shown), to generate electrical signals corresponding to the processed optical signals.

Each optical switching unit 110 comprises a respective polarization independent beamsplitter switch (PIBS) 120 optically coupled to a delay path apparatus 160. Each PIBS 120, as illustrated in FIGS. 2(A)-2(B), typically comprises an input switch unit 130 optically coupled to a spatial light modulator 140 which is in turn optically coupled to an output switch unit 150. Input switch unit 130 comprises an input polarizing beamsplitter (PBS) 132 coupled to an associated reflector 134; output switch unit 150 similarly comprises an output PBS 152 coupled to an associated reflector 154. For purposes of explanation of the present invention, and not limitation, a cube PBS is described in which light is typically deflected at 90o angles, dependent on its linear polarization. Alternatively, other types of PBSs can be used, such as Thompson PBSs, in which the deflection angle of linearly polarized light is other than 90o, with the appropriate adjustment of the optical architecture to adjust for the different light paths. As used herein, "PBS" refers to the entire PBS assembly, not just the interface of the prisms at which light beam separation occurs.

Spatial light modulator 140 typically comprises a two-dimensional array of liquid crystal pixels which are individually controllable and comprise nematic liquid crystals, ferro-electric liquid crystals, or the like. Each pixel is

illuminated by at least one light beam passing from light source 105 (for ease of discussion, it will be assumed that one light beam passes from each pixel). The pattern of the two-dimensional (2-D) array of liquid crystal pixels in SLM 140 corresponds to the desired electrical output; for example, the pattern typically corresponds to the 2-D array of antenna elements that are independently actuated by signals generated by optical signal processing system 100 (FIG. 1).

Each delay path apparatus 160 (FIG. 1) comprises a mirror prism 162, or alternatively, a similar light deflection device such as a fiber optic cable 164 (illustrated in delay assembly 1103) or the like. A lens 166 such as a GRIN (graded index) such as a SELFOC lens or the like, is advantageously used to couple each end of the optical fiber to the respective PIBS. Each delay path apparatus 160 is coupled to a respective PIBS 120 such that light passing along a selected axis from output switch unit 150 of that PIBS is directed along a delay path in which the light is deflected and enters the respective input switch unit 130 of the PIBS in the next sequential optical switching unit. The distance between the mirror prism 162 and the associated PIBS to which it is coupled, or the length of fiber optic cable 164, as appropriate, determines the length of the delay path that the deflected light beam must travel before entering the next sequentially coupled optical switching unit and determines the amount of time delay a particular delay assembly 110 imparts to a deflected beam.

In FIG. 1 each delay path apparatus 160 is illustrated with a gap, such as an air gap, between it and the associated PIBS; alternatively, the coupling of light beams between the associated PIBS and mirror prism 162 may be via glass or the like (not shown) which has an optical index substantially the same as the material of which output PBS 152 is made. Additional optical devices such as lenses (not shown) can also be disposed in the path between the respective PIBSs and delay path apparatus coupled thereto in order to ensure that the plurality of light beams passing through the optical signal processing system remain aligned along selected paths such that they each pass through predetermined pixels in each SLM in each PIBS in the cascade.

Collimation of the plurality light beams passing through the cascade of optical switching units is desirable to minimize crosstalk. An optical lens 170, or alternatively a lens array, can be advantageously optically coupled in the optical architecture between optical switching units to maintain the collimation of the lights. Additional lenslet arrays 170 can be disposed in delay path apparatus as illustrated in optical switching unit 1102 in FIG. 1.

The conventional PIBS illustrated in FIGS. 2(A)-2(D) enables non-polarized light incident on a first or a second input face 135, 137, respectively, on the switch to be selectively switched to either a first or a second output face 155, 157, respectively. By way of example and not limitation, a representative unpolarized light beam "B" is illustrated in FIG. 2(A) incident on first input face 135 of PIBS 120. This unpolarized light beam comprises both "p" polarized, or horizontally linearly polarized (the electric vector of the light is parallel to the plane of incidence, i.e., the plane of the page as illustrated in FIGS. 2 and indicated by the twin headed arrows shown on the light beam line), and "s" polarized, or vertically linearly polarized, i.e., oriented orthogonal to the plane of the page, as illustrated by the dots in the Figure.

Beam B is split into constituent beams of opposite linear polarization in PBS 132, noted in FIG. 2(A) as B' and B". Beam B' passes through input switch unit 130 along substantially the same path as incident beam B and into a respective pixel in SLM 140; beam B" is deflected in PBS 132 such that it is incident on reflector 134 and deflected further into a different respective pixel in SLM 140. In FIG. 2(A)-2(D), cube PBSs are shown, hence the angles of deflection are typically about 90o. As illustrated in FIG. 2(A), the two respective pixels in SLM 140 through which beams B' and B" pass are set to not cause a polarization rotation, thus the constituent light beams B' and B" maintain their original respective linear polarizations as they emerge from SLM 140 into output switch unit 150. Beam B' is incident on reflector 154 and is deflected into output PBS 152; beam B" passes from SLM 140 directly into output PBS 152. The polarization of beam B' is such that when it is incident on the beamsplitter in PBS 152, it passes directly through undeflected; by contrast, beam B", which is of the opposite linear polarization, is deflected when it strikes the beamsplitter in PBS 152 and thus the two constituent beams are again combined into one unpolarized beam B that passes from output PBS 152 through first output face 155 and that is oriented (e.g., as illustrated, perpendicular) along a path which is orthogonal to the path of the incident light beam on first switching unit 130.

FIG. 2(B) illustrates PIBS 120 with the respective pixels in SLM 140, through which the polarized constituent beams of incident light beam B pass, set to cause a 90o polarization rotation. The operation is as described above with the exception that beam B' undergoes a 90o polarization shift in SLM 140 from p-polarized to s-polarized, and thus when this beam is deflected into output PBS 152 by reflector 154, beam B' is again deflected by 90o towards second output face 157. Similarly, beam B" is shifted from s-polarized to p-polarized light in SLM 140 and thus passes directly through output PBS 152 to be combined with beam B'. The recombined beam B passes from second output face 157.

FIGS. 2(C) and 2(D) illustrate the operation of PIBS 120 with SLM 140 pixels set for no rotation and 90o rotation, respectively, when light beam B is incident on input switching unit 130 through second input face 137. The operation is identical to that described above with the exception that the no-polarization rotation SLM 140 setting results in the output beam emerging from second output face 157 and the polarization-rotation SLM 140 setting results in recombined beam B emerging from first output face 155.

In accordance with this invention, a plurality of optical switching units 110 are sequentially coupled together as illustrated in FIG. 1 such that light emerging from one of the two output faces of the respective PIBS 120 is directed along a delay path into the respective delay path apparatus 160, or alternatively, light emerging from the other output face of the PIBS passes along a direct path into the PIBS of the next succeeding optical switching unit in the cascade. As described above, the output face from which recombined beam B passes from the PIBS for a beam incident on a given input face is selected by the settings of the SLM pixels through which the constituent beams pass in the PIBS.

For example, as illustrated in FIG. 1, light source 105 is optically coupled to first optical switching unit 1101 such that unpolarized collimated light beams are incident on input switching unit 130 of first switching unit PIBS 1201.(for ease of discussion, particular components in a given optical switching unit will be referenced by the subscript of the respective optical switching unit). The respective pixels in SLM 140 in first switching unit PIBS 1201 are

set to cause a polarization rotation such that the recombined beam passes from output switching unit 150 along an axis that constitutes the direct path into second optical switching unit 1102. In second optical switching unit PIBS 1202, respective pixels in the SLM are set such that the polarization of light beams passing therethrough is not changed; as a consequence, the recombined beam B passes from output switching unit 150 in PIBS 1202 along a delay path axis that directs the beam into delay path apparatus 1602. The light beam is deflected in delay path apparatus 1602 such that it is incident on input switching unit 130 of PIBS 1203 in third optical switching unit 1103.

In operation, a plurality of light beams necessary for generating the necessary control signals for the device in which this system is employed, such as a phased array radar, pass simultaneously into the first optical switching unit. Respective manipulation of the linear polarization of the polarized constituent beams from each light beam in the PIBS of each optical switching unit determines whether a respective light beam passes along the delay path or the direct path in a given optical switching unit. The cumulative effect of these manipulations provides, at the output of the cascade of optical switching devices, a plurality of differentially time delayed optical signals. Conversion of these optical signals into corresponding electrical signals in converter 200 produces electrical signals that, for example, differentially actuate a predetermined ones of the elements in an antenna array.

A second embodiment of the present invention is illustrated in FIG. 3. The components in this embodiment are as described above with respect to FIGS. 1 and 2 with the exception that in each optical switching unit 110 the delay path (illustrated comprising fiber optic cable delay units 164) directs light from a predetermined one of the output faces of output switching unit 150 of the respective PIBS into a predetermined one of the input faces of input switching unit 130 of the same PIBS. Each optical switching unit is thus independent, or self contained, in so much as only one optical coupling is necessary between optical switching units sequentially coupled in a cascade arrangement, with both delayed and undelayed light beams passing along the same coupling between optical switching units. As illustrated in FIG. 3, first optical switching unit 1101 is disposed such that incident unpolarized light beams from the light source or a preceding switching unit enter input optical switching unit 130 through first input face 135. Delay path apparatus 1601 is coupled between first output face 155 of output switching unit 150 in PIBS 1201 and second input face 137 of input switching unit 130 in PIBS 1201. Second output face 157 of second switching unit 150 in PIBS 1201 is coupled to first input face 135 of PIBS 1202 in second switching unit 1102.

In operation, the incident unpolarized light beam enters first PIBS 1201 and is directed to either first output face 155 or second output face 157 dependent on whether the polarization of the constituent beams is rotated as these beams pass through SLM 140 in PIBS 1201. As illustrated in FIG. 3, the pixels in SLM 140 in. PIBS 1201 are controlled to cause a polarization shift of 90o, and thus the recombined beam from output switching unit 150 of PIBS 1201 passes from second output face 157, which is coupled to provide the direct path to second optical switching unit 1102. For purposes of illustration, second PIBS 1202 is shown in FIG. 3 configured to switch the incident light beam into the delay path (the path of the incident beam is illustrated by a solid dark line). The SLM is controlled so as to not cause a rotation in the polarization of the respective constituent light beams passing through PIBS 1202 such that the recombined light beam is deflected to first output face 155 (in output switching unit 150 in

PIBS 1202), at which point it passes along the delay path into delay path apparatus 1602 and is directed via fiber optic delay line 164 into second input face 137 of input switching unit 130 in PIBS 1202 (the path of the delayed optical signal is shown as a dashed line, which, for purposes of illustration only, is shown slightly offset from the solid line representing the incident beam). The unpolarized light passing from the delay path again passes through PIBS 1202, in which the respective pixels in the SLM are still set to cause polarization rotation of the constituent light beams passing therethrough. The light passing from the delay path is recombined in a beam that is directed to second output face 157 as it exits PIBS 1202 into PIBS 1203. The light beam can thus pass down the cascade and be time delayed as desired dependent on the settings of the pixels in each respective SLM in the respective optical switching units in the cascade.

The arrangement of FIG. 3 thus provides an independent optical switching unit that is readily coupled with similar units to form a cascade of sequentially coupled optical switching units.

A third embodiment of the present invention is illustrated in FIGS. 4(A) and 4(B). The components in this embodiment are as described above with respect to FIGS. 1 and 3 except as noted in the following discussion. In this embodiment a plurality of optical switching units 110 are sequentially optically coupled together in a cascade along a first axis "A" in the plane of the drawing. Each optical switching unit comprises a respective PIBS 120 and a respective delay path apparatus 160 comprising, e.g., a mirror prism 162 (alternatively, a fiber optic cable can be used for directing light beams along the delay path). Further, a plurality of corner prisms 480 are coupled between respective output switching units 150 and input switching units 130 of sequentially coupled optical signal switching units 110 to deflect light passing from the PIBS in one switching unit into the PIBS in the next sequential optical switching unit such that the light is translated along first axis "A" between respective ones of the optical switching units.

The delay path apparatus associated with each optical switching unit 110 is disposed along a second axis "B" illustrated in FIG. 4(B). Axis "B" lies in a plane orthogonal to the plane of the first axis "A" (i.e., extending out of the plane of page of FIG. 4(A)) such that light deflected onto the delay path is deflected along the second axis into the respective delay path apparatus and thence into the input optical switching unit of the PIBS in the next sequential optical switching unit 110 (the portion of the delay path along the axis "A", i.e., that portion in which light in the delay path is translated along axis "A" to be aligned to enter the next sequential optical switching unit is illustrated in FIG. 4(A) as dashed lines across the respective output switching unit). Light passing through a cascade having this arrangement is thus deflected along three mutually orthogonal axes, that is axis "A" in the plane of FIG. 4(A), axis "B" extending out of the plane of FIG. 4(A), and through respective PIBSs ("up" and "down" in the plane of FIG. 4(A) between respective alternating corner prisms 480).

Individual components of each PIBS can advantageously be fabricated as a part of a larger block of that type of component. For example, input switching unit 130 in PIBS 1201 in first optical switching unit 1101 advantageously constitutes a portion of a first switching unit block 430, that is an integral elongated block comprising a beamsplitter and associated reflector, such that one block can be fabricated and segments of the block can then provide at least a

portion of the respective switching units for PIBSs in sequentially coupled optical switching units. As the input and output switching units in each PIBS are structurally the same, portions of first switching unit block 430 comprise the input switching block of, e.g., first optical switching unit 11 01, and the contiguous portion comprises output switching unit 150 of second optical switching unit 1102 and so forth in an alternating fashion. A second switching block 450 is disposed to provide output switching unit 150 of first optical switching unit 1101; in the arrangement illustrated in FIGS. 4(A) and 4(B) the next sequential portion of block 450 forms the input optical switching unit for optical switching unit 1102. Similarly, respective SLMs in each PIBS advantageously constitute a portion of a polarization rotation switch block 440. Switch block 440 comprises an elongated substrate on which respective arrays of liquid crystals are disposed with the associated address circuitry for individual pixels. Switch block 440 is optically coupled to first switching unit block 430 and second switching unit block 450 to form a block PIBS, with individual segments of that block constituting the respective PIBSs in the cascade of optical switching units.

In this "folded" or integrated arrangement illustrated in FIGS. 4(A) and 4(B) light is directed along three mutually orthogonal axes (two perpendicular axes in the plane of FIG. 4(A), and another extending out of the plane of FIG. 4(A)) as it passes along the respective direct paths, delay paths, and inter-switching unit coupling segments. This arrangement allows compact packaging of a cascade of optical signal switching units and presents an arrangement that is readily fabricated with the use of the beamsplitter and polarization rotation switch blocks.

A still further embodiment of this invention is illustrated in FIG. 5. The cascade arrangement of optical switching units illustrated in this Figure provides for switching of the processed light beams in two dimensions (that is, the device is not "folded" as described above with respect to FIG. 4). In this arrangement the respective PIBSs advantageously comprise portions of a first block switching unit 530, a block polarization rotation switch 540, and a second block switching unit 550 as described above with respect to the device illustrated in FIGS. 4(A) and 4(B). Each respective optical switching unit 110 comprises a respective PIBS 520, and a delay path path apparatus 560 comprising a mirror prism or the like, such as a fiber optic delay line as described above with regard to FIG. 1. A plurality of optical switching units are sequentially optically coupled,. and at least a portion of the respective PIBSs are aligned along a first axis noted in FIG. 5 by the letter "A". Respective delay path apparatuses in alternating ones of optical switching units are disposed on opposite sides of the plurality of respective PIBSs disposed along first axis A.

In operation, light beams incident on the cascade of optical switching devices pass into first optical switching unit 1101 and are directed by PIBS 5201 onto a direct path to enter the next sequential optical switching unit 1102 or onto a delay path into respective delay path apparatus dependent on the polarization rotation selected for the SLM in PIBS 5201, as described above. This arrangement facilitates fabrication of a cascade of optical switching units as a polarization rotation switch block can be used for at least portions of the plurality of SLMs in respective sequentially coupled optical switching units.

Each of the embodiments described above further has a structure that is readily adapted to fabricating a device having relatively small time delays, that is, the length of the delay path can be made relatively short. Short

delay times are advantageous in allowing the use of higher frequencies in phased array radars. In each of the embodiments of this invention, the delay path apparatus can be disposed in close physical proximity to the polarizing beamsplitter/spatial light modulator combinations to provide an optical switching unit capable of generating a relatively short time (e.g., picosecond or shorter) delay in an optical signal. Further, close proximity of the delay path apparatus with the respective PBSs and SLMs makes possible a structure in which there is a minimal or no air gap between the delay path assembly and the PBS, which reduces the possibility of light beams being deflected in passing from one optical medium, e.g., the glass of the PBS, through air, to a second optical medium, such as the glass of the mirror prism assembly.

While only certain features of the invention have been illustrated and described herein, many modifications and changes will occur to those skilled in the art. It is, therefore, to be understood that the appended claims are intended to cover all such modifications and changes as fall within the true spirit of the invention.

CLAIMS: What is claimed is:

[*1] 1. An optical signal control system comprising a polarization independent beamsplitter switch (PIBS) and a delay path apparatus, said delay path apparatus being optically coupled to said PIBS, said PIBS and said delay path apparatus together comprising an optical switching unit.

[*2] 2. The system of claim I wherein said PIBS comprises:

an input switch unit having an input polarizing beam splitter (PBS);

a spatial light modulator (SLM) optically coupled to said input switch unit; and

an output switch unit having an output PBS, said output switch unit being optically coupled to said SLM.

[*3] 3. The system of claim 2 wherein said input PBS comprises a cube polarizing beam splitter having mutually orthogonal first and second input axes, and an optical deflector disposed to deflect incident light beams into said SLM;

said output PBS comprising a cube polarizing beam splitter having mutually orthogonal first and second output axes and an optical deflector disposed to deflect light beams passing from said SLM along a selected path into said output PBS such that incident light passes from said PIBS along either a direct path or a delay path dependent on the input axis along which the incident light enters said input switching unit and the polarization rotation imparted by the SLM pixels to light passing therethrough.

[*4] 4. The system of claim 3 wherein said SLM comprises an array of independently controllable liquid crystal pixels.

[*5] 5. The system of claim 4 wherein said delay path apparatus comprises a light deflection device selected from the group consisting of prisms, mirrors, and optical fibers.

[*6] 6. An optical signal control system comprising a plurality of optical switching units sequentially optically coupled in a cascade; each of said optical switching units comprising a polarization independent beamsplitter switch (PIBS) and a delay path apparatus, said delay path apparatus being optically coupled to said PIBS,

[*7] 7. The system of claim 6 wherein said PIBS comprises:

an input switch unit having an input polarizing beam splitter (PBS);

a spatial light modulator (SLM) optically coupled to said input switch unit; and

an output switch unit having an output PBS, said output switch unit being optically coupled to said SLM.

[*8] 8. The system of claim 7 wherein said SLM comprises an array of independently controllable liquid crystal pixels.

[*9] 9. The system of claim 8 wherein said delay path apparatus comprises a light deflection device selected from the group consisting of prisms, mirrors, and optical fibers.

[*10] 10. The system of claim 9 wherein one of said delay path apparatuses is coupled between the output PBS of its respective optical switching unit and the input PBS of the next sequential optical switching unit in the cascade.

[*11] 11. The system of claim 9 wherein at least one of said delay path apparatuses is coupled between the the output PBS of its respective optical switching unit and a selected one of the input axes of the respective input PBS of said respective switching unit.

[*12] 12. The system of claim 10 wherein each of said optical switching units is disposed along a first axis.

[*13] 13. The system of claim 12 wherein at least a portion of input and output switch units in respective ones of said plurality of sequentially coupled optical switching units comprise respective sequentially adjoining contiguous segments of a switching unit block.

[*14] 14. The system of claim 12 wherein at least a portion of SLMs in respective ones of said sequentially coupled optical switching units comprise respective sequentially adjoining contiguous segments of a polarization rotation switch block.

[*15] 15. The system of claim 13 wherein each of said delay path apparatuses is coupled to respective optical switching units along an axis disposed orthogonally to said first selected axis.

[*16] 16. The system of claim 15 wherein each of said delay path apparatuses is oriented along a second selected axis.

[*17] 17. The system of claim 16 wherein said second selected axis is orthogonal to said first selected axis.

[*18] 18. The system of claim 17 wherein said first and second selected axes are coplanar.

[*19] 19. The system of claim 11 wherein at least one of said delay assemblies is disposed with respect to PIBSs to which it is coupled such that substantially no air gap exists at the coupling between said delay path apparatus and corresponding ones of said PBSs.

[*20] 20. The system of claim 6 further comprising a lens optically coupled to one of said optical switching units and disposed to collimate light beams passing therethrough.

Pat. No. 5463497 printed in FULL format.

5,463,497

<=2> GET 1st DRAWING SHEET OF 12

Oct. 31, 1995

Illumination device including an optical integrator defining a plurality of secondary light sources and related method

INVENTOR: Muraki, Masato, Yokohama, Japan
Suzuki, Akiyoshi, Tokyo, Japan
Imai, Shunzo, Yamato, Japan

ASSIGNEE-AT-ISSUE: Canon Kabushiki Kaisha, Tokyo, Japan (03)

APPL-NO: 261,229

FILED: Jun. 16, 1994

CERTCORR: Mar. 26, 1996 a Certificate of Correction was issued for this Patent

FOR-PRIOR:
Jun. 8, 1989 Japan 1-146216
Jan. 20, 1990 Japan 2-011534
Mar. 1, 1990 Japan 2-050587

REL-US-DATA:
Continuation of Ser. No. 918,005, Jul. 24, 1992 now abandoned Which is a division of Ser. No. 534,246, Jun. 7, 1990 now patented 5,153,773

INT-CL: [6] G02B 27#10; F21K 7#00

US-CL: 359#618; 359#619; 362#259; 362#268;

CL: 359;362;

SEARCH-FLD: 359#618, 619, 638, 639, 640, 621, 622, 623; 362#259, 268

REF-CITED:

U.S. PATENT DOCUMENTS

3,670,260	6/1972	* Koester et al.	331#94.5
4,367,009	1/1983	* Suzki	360#6.5
4,370,026	1/1983	* Dubroeucq et al.	350#163
4,458,994	7/1984	* Jain et al.	354#4
4,497,013	1/1985	* Ohta	362#32
4,497,015	1/1985	* Konno et al.	362#268
4,498,742	2/1985	* Uehara	350#523
4,619,508	10/1986	* Shibuya et al.	353#122
4,793,694	12/1988	* Liu	350#379
4,811,328	3/1989	* Ito et al.	369#112
4,851,978	7/1989	* Ichihara	362#268
4,918,583	4/1990	* Kudo et al.	362#268
4,939,630	7/1990	* Kikuchi et al.	362#268
4,974,919	12/1990	* Muraki et al.	350#6.6

5,016,149	5/1991	* Tanaka et al.	362#259
5,048,926	9/1991	* Tamimoto	359#618
5,091,744	2/1992	* Omata	355#53

FOREIGN PATENT DOCUMENTS

31969	4/1973	* Japan
111832	9/1979	* Japan
59-226317	12/1984	* Japan
162218	8/1985	* Japan
32555	2/1988	* Japan

PRIM-EXMR: Sugarman, Scott J.

ASST-EXMR: Papalas, Michael A.

LEGAL-REP: Fitzpatrick, Cella, Harper & Scinto

CORE TERMS: integrator, laser, beam, reticle, lens, secondary, intensity, prism, light source, laser beam, illumination, fringe, optical path, phase, inputted, wedge-shaped, wafer, illuminated, condenser, mirror, polarization, schematic, plane, excimer, illuminance, exposure, flat, deflector, plural, projection

ABST:
An illumination device includes a radiation source; an optical integrator having an array of lenses disposed along a plane perpendicular to an optical axis of the device; a first optical system for amplitude-dividing a coherent beam from the radiation source and producing plural beams which are substantially incoherent with each other, the first optical system also being effective to project the beams to the optical integrator in different directions and to superpose the beams upon one another on the optical integrator; and a second optical system for directing beams from the lenses of the optical integrator to a surface to be illuminated and for superposing the beams upon one another on the surface to be illuminated.

NO-OF-CLAIMS: 38

EXMPL-CLAIM: <=20> 1

NO-OF-FIGURES: 33

NO-DRWNG-PP: 12

PARCASE:

This application is a continuation of prior application Ser. No. 07/918,005 filed Jul. 24, 1992, now abandoned, which application is a divisional of prior application Ser. No. 07/534,246, filed 6/7/90 now U.S. Pat. No. 5,153,773.

SUM:

FIELD OF THE INVENTION AND RELATED ART

This invention relates to an illumination device and, more particularly, to an illumination device suitably usable in an exposure apparatus for manufacture of semiconductor microcircuits, for illuminating a circuit pattern of a mask or a reticle.

Many attempts have been made to develop an exposure apparatus having a coherent light source such as an excimer laser, for example. As a problem raised when a circuit pattern of a mask or reticle is irradiated with a light beam from a coherent light source, there is non-uniformness in the illuminance distribution upon the mask or reticle. This non-uniformness attributes to an interference fringe formed by the light beam from the coherent light source. Thus, in order to avoid such non-uniformness in the illuminance distribution resulting from the interference fringe, many types of illumination devices have been attempted.

SUMMARY OF THE INVENTION

The present invention is concerned with improvements in this type of illumination device, and it is accordingly an object of the present invention to provide an illumination device by which a surface to be illuminated, such as the surface of a mask or reticle, can be illuminated in the manner best suited to the manufacture of semiconductor microcircuits, for example.

In accordance with an aspect of the present invention, to achieve the above object, there is provided an illumination device, comprising: a radiation source; an optical integrator having an array of lenses disposed along a plane perpendicular to an optical axis of said device; a first optical system for amplitude-dividing a coherent beam from said radiation source and producing plural beams which are substantially incoherent with each other, said first optical system also being effective to project the beams to said optical integrator in different directions and to superpose the beams upon one another on said optical integrator; and a second optical system for directing beams from said lenses of said optical integrator to a surface to be illuminated and for superposing the beams upon one another on the surface to be illuminated.

Also, in accordance with another aspect of the present invention, there is provided an illumination device, comprising: a radiation source for supplying a radiation beam having an asymmetrical intensity distribution; and an illumination optical system for amplitude-dividing the radiation beam into first and second beams and for superposing the first and second beams upon one another so that the first beam is inverted relative to the second beam, to thereby produce a third beam having an intensity distribution which is symmetrical with respect to an optical axis of said illumination optical system, wherein the third beam is directed to a surface to be illuminated to illuminate the same.

These and other objects, features and advantages of the present invention will become more apparent upon a consideration of the following description of the preferred embodiments of the present invention taken in conjunction with the accompanying drawings.

DRWDESC:

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a schematic view showing a general structure of an illumination device according to an embodiment of the present invention.

FIGS. 2A-2E are graphs, respectively, showing light intensity distributions upon sections on the laser light path and upon a reticle surface, in the device shown in FIG. 1.

FIGS. 3A and 3B are schematic views, respectively, showing a modified form of the FIG. 1 device.

FIG. 4 is a chart showing forms arranged in accordance with the present invention.

FIG. 5 is a schematic view showing a general structure of an illumination device according to another embodiment of the present invention.

FIGS. 6A-6E are graphs, respectively, showing light intensity distributions upon some sections on the path of laser light and upon a reticle surface, in the device shown in FIG. 5.

FIG. 7 is a schematic view, illustrating in sections a laser beam from a laser source and four laser beams formed by dividing the laser beam from the laser source, in the illumination device of the FIG. 5 embodiment.

FIG. 8 is a schematic view showing a general structure of an illumination device according to a further embodiment of the present invention.

FIGS. 9A-9C are schematic views, respectively, showing examples of a beam inversion optical system.

FIG. 10 is a schematic view showing an example wherein a pair of beam inversion optical systems are arrayed two-dimensionally.

FIG. 11 is a schematic view showing a modified form of the optical arrangement of the FIG. 9A example.

FIG. 12 is a schematic view showing an example wherein a pair of beam inversion optical systems such as shown in FIG. 10 are coupled by a relay optical system.

FIG. 13 is a schematic view showing an example of the relay optical system in FIG. 12.

FIG. 14 is a schematic view showing another example wherein a plurality of beam inversion optical systems are used.

FIGS. 15 and 16 are schematic views, respectively, illustrating the relationship between the state of impingement of plural light beams on an optical integrator and the illuminance distribution on the surface being illuminated.

FIGS. 17A-17C are schematic views, respectively, each showing a beam inversion optical system including a phase shift plate.

FIG. 18 is a schematic view showing an example wherein a plurality of beam inversion optical systems each having a phase shift plate, are used.

FIGS. 19A and 19B are schematic views, respectively, each showing an example of a shift phase plate.

DETDESC:

DESCRIPTION OF THE PREFERRED EMBODIMENTS

FIG. 1 is a schematic view showing a general structure of an illumination device according to an embodiment of the present invention. In this embodiment, the invention is applied to a reduction projection type exposure apparatus, called a "stepper".

In FIG. 1, denoted at 11 is a KrF excimer laser having a relatively small spatial coherency (i.e. a relatively large number of transverse modes); at 20 is a light dividing and incoherence-transformation optical system; at 22 is an optical integrator having an array of bar lenses, arrayed along a plane perpendicular to the optical axis of the illumination device; at 23 is a condenser lens; at R is a reticle (or mask) having a circuit pattern formed thereon; at W is a wafer having a resist applied thereto; and at 24 is a reduction projection lens system for projecting the circuit pattern of the reticle R onto the wafer W. The optical system 20 includes a half mirror (prism) 12, mirrors (rectangular prisms) 13, 14 and 15, wedge-shaped prisms 16 and 17, and another wedge-shaped prism 21 which is rotatable when actuated by a driving means 210. The optical system 20 functions to amplitude-divide laser light from the laser 11 and to provide a plurality of mutually incoherent light beams to the optical integrator 22. While the optical system 20 has additional functions, other than this, those functions will be descried later in detail.

FIGS. 2A-2E illustrate light intensity distributions upon sections A-D (planes perpendicular to the sheet of the drawing) and upon the reticle R surface, on the path of the laser light in the device of FIG. 1. Referring to FIGS. 1 and 2A-2E, the illumination device of the present embodiment will be explained in detail.

Parallel laser light emanating from the laser 1 enters the half mirror 12, by which the laser light is amplitude-divided into two light beams LB1 and LB2. The light beam LB1 passed through the half mirror 12 goes straight toward the wedge-shaped prism 17 while, on the other hand, the light beam LB2 reflected by the half mirror 12 is further reflected by the mirrors 13, 14 and 15 in this order so that its path is bent three times, each at a right angle, and thereafter it goes to the wedge-shaped prism 16. There is a difference in length between the optical path for the light beam LB1 impinging on the wedge-shaped prism 17 and the optical path for the light beam LB2 impinging on the wedge-shaped prism 16. The optical system 20 is arranged so that the difference in optical path length between the light beams LB1 and LB2 is not shorter than the temporal coherence length of the laser light as determined by the wavelength range of the laser light (i.e. light beams LB1 and LB2). Accordingly, there occurs substantially no interference between the light beams LB1 and LB2 as deflected by the wedge-shaped prisms 16 and 17, respectively. Namely, these light beams are substantially incoherent with each other.

As described hereinbefore, the excimer laser 11 used in the present embodiment has a relatively small spatial coherency. However, for reduction of chromatic aberration to be produced by the projection lens system 24, a band narrowing element such as an etalon, prism or the like is used to narrow the

wavelength range (bandwidth) of the laser light extremely. For this reason, the temporal coherency is large. Since in the present embodiment a laser light of a center wavelength lambda = 248.4 nm and a wavelength range DELTA lambda = 0.003 nm is used, the temporal coherence length of the laser beams LB1 and LB2 is relatively long. In consideration thereof, by imparting an optical path difference to the light beams LB1 and LB2, mutually incoherent light beams are produced and directed to the optical integrator 22 so as to avoid formation of an interference fringe on a light receiving surface of the optical integrator 22, or to reduce the contrast of an interference fringe, if any, on the light receiving surface of the optical integrator. This will be described later in more detail.

Each of the light beams LB1 and LB2 deflected (refracted) by the wedge-shaped prisms 16 and 17, respectively, is inputted to the wedge-shaped prism 21 in the form of parallel light. Since the wedge-shaped prism 21 is being rotated by the driving means 210 about the optical axis of an optical system comprising the condenser lens 23 and the projection lens system 24, the path of each of the light beams LB1 and LB2 passing through the wedge-shaped prism 21 and impinging on the light receiving surface of the optical integrator 22 as well as the position of incidence thereof upon this light receiving surface, change with time.

Here, the wedge-shaped prisms 16, 17 and 21 are so arranged that the light beams LB1 and LB2 always partially overlap one upon another, on the light receiving surface of the optical integrator 22.

As shown in FIG. 2A, the laser light from the laser 11 has a sectional intensity distribution which is in the form of or similar to a Gaussian distribution. Thus, as shown in FIG. 2B, each of the light beams LB1 and LB2 impinging on the wedge-shaped prisms 16 and 17 has a sectional intensity distribution in the form of a Gaussian distribution. When these light beams LB1 and LB2 are inputted to the light receiving surface of the optical integrator 22 and partially overlap one upon another, the combined light has a sectional intensity distribution which, as shown in FIG. 2C, is symmetrical with respect to the optical axis and, additionally, it is substantially uniform. This is the effect of partial overlapping of the light beams LB1 and LB2 on the light receiving surface of the optical integrator 22 as described. Also, in the neighborhood of the light emitting portion of the optical integrator 22, i.e., in the section D, there is produced a light intensity distribution such as shown in FIG. 2D. It is to be noted here that preferably the light beams LB1 and LB2 should be so superposed one upon another on the light receiving surface of the optical integrator 22 that, even if in the section B the light beams LB1 and LB2 have sectional intensity distributions of the form other than the Gaussian distribution, still a uniform intensity distribution is provided on the light receiving surface (plane C) of the optical integrator 22.

The uniformness in illuminance distribution upon the reticle R surface is proportional to the uniformness in light intensity distribution on the light receiving surface of the optical integrator 22 and the number of the lens elements constituting the optical integrator 22. On the other hand, when a plurality of coherent light beams such as the light beams LB1 and LB2 are inputted to an optical integrator, the larger the number of lens elements to which a single light beam is inputted, the larger is the number of mutually coherent secondary light sources formed in the neighborhood of the light emitting end of the optical integrator. Mutually coherent light beams from

these secondary light sources easily interfere with each other to form an interference fringe of high contrast on the surface of a reticle. Since the optical integrator has a function for dividing the wavefront of a received light beam, the contrast of such an interference fringe is determined by the degree of spatial coherency of the laser.

In the present embodiment, as the laser 11, a laser having small spatial coherency is used and, in place of increasing the number of lens elements of the optical integrator 22, the optical arrangement is structured so that some lens elements receive both the light beams LB1 and LB2 to thereby increase the number of formed secondary light sources, to thereby avoid that an interference fringe, if any, formed on the reticle R damages the uniformness in illuminance distribution upon the reticle R. Further, since the light beams LB1 and LB2 are projected to the optical integrator 22 in different directions, interference fringes of low contrast, if any, formed by the light beams LB1 and LB2 on the reticle R surface, have different phases. This results in a smoothing affect on the light intensity distribution as determined by these interference fringes, and therefore, the formation of interference fringes does not so influence the illuminance distribution on the reticle R surface.

Further, in the present embodiment, the wedge prism 21 is rotated to thereby shift the paths for the light beams LB1 and LB2 impinging on the optical integrator 22 as well as their positions of incidence upon the optical integrator. Accordingly, the light intensity distribution to be formed on the light receiving surface of the optical integrator 22 has such a shape as formed by superposing plural light intensity distributions formed successively. This attains further enhancement of uniformness. Also, in the neighborhood of the light emitting surface of the optical integrator, the light beams LB1 and LB2 provide a distribution of secondary light sources (i.e. an effective light source) which change with time. Accordingly, the number of secondary light sources increases substantially.

Since the excimer laser 11 is a pulsed laser, it emits pulsed laser light at preset time intervals. When the number of laser pulses necessary for printing, by exposure, the circuit pattern of the reticle R onto the resist layer of the wafer W is denoted by M, if during the exposure the wedge prism 21 is rotated continuously, the light intensity distribution on the light receiving surface of the optical integrator 22 has such a shape as formed by superposing light intensity distributions of a number M, one upon another. Further, if the light beams LB1 and LB2 produce secondary light sources of a number N per one laser pulse, then the wafer W is exposed with the lights from the secondary light sources of a number "M x N".

Next, the optical arrangement following the optical integrator 22 will be explained in detail.

The condenser lens 23 comprises a lens assembly constituted by plural lens elements disposed along the optical axis, and it serves to direct, toward the reticle R, the light beams from a large number of secondary light sources as formed in the neighborhood of the light emitting surface of the optical integrator 22. The secondary light sources of a large number are distributed in a plane perpendicular to the optical axis of the condenser lens 23, and the spacing between this plane (secondary light source forming plane) and the light entrance side (front) principal plane of the condenser lens 23 is equal to the focal length of the condenser lens 23. On the other hand, the spacing between

the light exit side (rear) principal plane of the condenser lens 23 and the reticle R is set to be equal to the focal length of the condenser lens 23. In this structure, each of the light beams from the secondary light sources of a large number, is transformed by the condenser lens 23 into parallel light, and the resultant parallel light beams are efficiently superposed one upon another on the reticle R surface. The illuminance distribution on the reticle R at this time is satisfactorily uniform, as illustrated in FIG. 2E.

Similarly, the projection lens system 24 comprises a lens assembly constituted by plural lens elements disposed along the optical axis, and it serves to bring the circuit pattern surface of the reticle R and the surface of the wafer W to be exposed, into an optically conjugate relationship. In the present embodiment, the structure is arranged so that the projection lens system 24 forms an image of the circuit pattern of the reticle R on the wafer W at a reducing magnification of 1:5. The projection lens system 24 has an entrance pupil (not shown) which is placed in an optically conjugate relationship with the secondary light source forming plane adjacent to the light emitting surface of the optical integrator 22. Thus, like the reticle R, the wafer W is illuminated in the manner of Kohler illumination.

The optical integrator 22 and the condenser lens 23 is arranged so as to bring the light receiving surface of the optical integrator 22 and the circuit pattern surface of the reticle R into an optically conjugate relationship.

As described in the foregoing, the illumination device of the present embodiment uses as a light source an excimer laser (11) having small spatial coherency and, through the optical system 20, mutually incoherent light beams LB1 and LB2 are inputted to the light receiving surface of the optical integrator 22 along different directions so that they are superposed partially one upon another. With this arrangement, quite a large number of secondary light sources can be formed in the neighborhood of the light emitting surface of the optical integrator 22 and, additionally, the intensity distribution on the light receiving surface of the optical integrator 22 can be made uniform. As a result, it is possible to provide an effective light source having closely distributed secondary light sources, and therefore, it is possible to illuminate the circuit pattern surface of the reticle R in the manner best suited for correct and accurate transfer of the circuit pattern of the reticle to the wafer, such that an image of the circuit pattern of the reticle R can be correctly and accurately printed on the wafer W.

The rotatable wedge prism 21 may be provided between the optical integrator 22 and the reticle R. Also, if in the optical path within the optical system 20 the diffraction loss of the light beam LB1 or LB2 is large, an imaging system such as a focal converter may be provided on the optical path so as to assure efficient transmission of the light beam LB1 or LB2 to the optical integrator 22. On that occasion, such an imaging system may be disposed so as to provide an optically conjugate relationship between the surfaces of predetermined optical elements, of the optical system 20, through which the light passes.

While in the present invention a light beam from a coherent light source such as a laser is amplitude-divided to provide a plurality of light beams, the number of such light beams is preferably about three (3) to twenty (20). By using light beams of a number within such a range, the optical system can be made relatively compact and, additionally, a satisfactory effective light source is obtainable.

Further, in the present invention, it is effective to use such a laser as having a large number of transverse modes and small spatial coherency and, particularly, good results are obtainable by using a laser (particularly an excimer laser) having a transverse mode of a number not less than one hundred (100). When an illumination device using such a laser as a light source is incorporated into a reduction projection type exposure apparatus, as in the FIG. 1 embodiment, it is possible to provide an exposure system having a good pattern transfer performance.

FIGS. 3A and 3B are schematic views, showing a modified form of the FIG. 1 device. In the embodiment shown in FIG. 1, for convenience in explanation, the optical system 20 is illustrated to be adapted to amplitude-divide the laser light into two (light beams LB1 and LB2). In reference to the present embodiment, however, the structure of such an optical system 20 adapted to amplitude-divide the light into four will be explained.

FIG. 3A illustrates details of a part of FIG. 1, from the optical system 20 to the reticle R. In this embodiment, the optical system 20 is constituted by half mirrors HM1 and HM2 and HM3; mirrors M1, M2, M3, M4 and M5; wedge-shaped prisms 16, 17, 18 and 19; and a rotatable wedge-shaped prism 21. Laser light LB0 emitted from a laser (not shown) has a sectional intensity distribution which is asymmetrical with respect to the optical axis of the illumination device. The laser light LB0 is amplitude-divided into four light beams, by means of a system constituted by the half mirrors (HM1, HM2 and HM3) and the mirrors (M1, M2, M3, M4 and M5), and each light beam is inputted to a corresponding one of the wedge-shaped prisms 16-19, such that light beams LB1, LB2, LB3 and LB4 emanate from these wedge-prisms 16-19, respectively. These light beams LB1-LB4 are incoherent with each other and, after passing through the wedge-prism 21, they are partially superposed one upon another on the light receiving surface of an optical integrator 22.

In the present embodiment, the optical arrangement is set so that each of the light beams LB1-LB4 is inputted to any four lens elements of the lens elements constituting the optical integrator 22 and that, on the light receiving surface of the optical integrator 22, partial overlapping is produced between the light beams LB1 and LB2; between the light beams LB1 and LB4; between the light beams LB2 and LB3; and between the light beams LB3 and LB4.

As best seen in FIG. 3B, the light beam LB3 is inverted relative to the light beam LB1 while, on the other hand, the light beam LB4 is inverted relative to the light beam LB2. Also, with respect to the horizontal direction or longitudinal direction in the sheet of the drawing, the light beams LB1-LB4 have different sectional intensity distributions. These light beams LB1-LB4 are projected to the optical integrator 22 along respective optical paths which are predetermined, so that a uniform light intensity distribution is produced on the light receiving surface of the optical integrator 22 and also that the interference fringes to be formed by these light beams are formed at different positions on the reticle R surface.

FIG. 4 is a chart illustrating examples according to the present invention, as Type 1-Type 7. In FIG. 4, row (I) corresponds to the sectional configuration of a portion of an optical integrator to which a predetermined single light beam as formed by the amplitude-division is inputted. Row (II) corresponds to the sectional configuration of the optical integrator as a whole, and row (III) corresponds to the state of superposition of the plural light beams upon the

light receiving surface of the optical integrator (wherein each dot represents the beam center). Row (IV) corresponds to an effective light source (distributed secondary light sources) as formed by a single laser beam pulse in the neighborhood of the light emitting surface of the optical integrator (wherein each dot represents one secondary light source), and row (V) corresponds to the number of the secondary light sources as formed by a single laser beam pulse in the neighborhood of the light emitting surface of the optical integrator. Type 1. In this chart corresponds to the arrangement having been described with reference to FIGS. 3A and 3B.

With the embodiments of the present invention as described in the foregoing, not only can a uniform illuminance distribution be provided on a surface being illuminated, such as the surface of a reticle or wafer, but also an effective light sources having a large number of distributed secondary light source can be formed in the optical path of the illumination device. Thus, it is possible to illuminate a surface, to be illuminated, satisfactorily. Accordingly, when the illumination device is used to illuminate a reticle or a wafer, it is possible to correctly and accurately transfer the circuit pattern of the reticle onto the wafer.

FIG. 5 is a schematic view showing a general structure of an illumination device according to another embodiment of the present invention. In this embodiment, the invention is applied to a reduction projection type exposure apparatus, called a "stepper".

In FIG. 5, light source 11 comprises a KrF excimer laser having a relatively small spatial coherency (i.e., having a relatively large number of transverse modes). The light source 11 produces a coherent parallel light (laser light).

Optical member 2 comprises a transparent parallel surface plate and is disposed tiltably. It serves to shift or translate the light from the laser 11, in a direction perpendicular to the optical axis of the illumination device. First beam splitter 3 serves to amplitude-divide the laser light passing through the optical member 2, into two light beams La and Lb (reflected light and transmitted light). The light beam La reflected by the first beam splitter 3 is again amplitude-divided by a second beam splitter 4a into two light beams La1 and La2 (reflected light and transmitted light). Of these light beams, the reflected light beam La1 is inputted to one wedge-shaped prism 8a1 of a first deflector 8, including four wedge-shaped prisms 8a1, 8a2, 8b1 and 8b2 and being adapted to deflect, by refraction, received plural light beams to superpose them one upon another. Denoted at 8c is a component of the first deflector 8, for mechanically coupling the four wedge-shaped prisms 8a1-8b2.

The light beam La2 transmitted through the second beam splitter 4a is reflected by reflection mirrors 5a, 6a and 7a in this order, whereby with respect to the cross-section of the light, it is rotated or inverted by 180 degrees relative to the light beam La1 and then is inputted to one wedge-shaped prism 8a2 of the first deflector 8.

On the other hand, the light beam Lb transmitted through the first beam splitter 3 is reflected by reflection mirrors 31 and 32, in this order, and then it is amplitude-divided again by a third beam splitter 4b into two light beams Lb1 and Lb2 (reflected light and transmitted light).

Of these light beams, the reflected light beam Lb1 is inputted to one wedge-shaped prism 8b1 of the first deflector 8. On the other hand, the light beam Lb2 transmitted through the third beam splitter 4b is reflected by reflection mirrors 5b, 6b and 7b in this order, whereby with respect to the cross-section of the light it is rotated or inverted by 180 degrees relative to the light beam Lb1, and then it is inputted to one wedge-shaped prism 8b2 of the first deflector 8.

The four light beams La1, La2, Lb I and Lb2 inputted to the first deflector 8 are refracted and deflected by the corresponding wedge-shaped prisms 8a1, 8a2, 8b1 and 8b2, respectively, and then they pass through a wedge-shaped prism (second deflector) 21 and are projected on the light receiving surface of the optical integrator 22 with overlapping. The optical integrator 22 comprises a plurality of bar lenses arrayed along a plane perpendicular to the optical axis of the illumination device. Here, the four light beams La1-Lb2 are incoherent with each other, as will be described later. The wedge-prism 21 is arranged to be rotated about the optical axis of a condenser lens 23, through a driving means 210.

In the neighborhood of the light emitting surface of the optical integrator 22, there is formed a secondary light source forming plane. In this plane, a large number of secondary light sources are formed, wherein the number is determined by the number of the bar lenses constituting the optical integrator 22 and the number of light beams inputted to the optical integrator. Under the influence of the condenser lens 23, the light beams from the light emitting surface of the optical integrator 22 are superposed one upon another on the surface of a reticle R, whereby the reticle R is illuminated with these light beams. Projection lens system 24 serves to project, in a reduced scale, a circuit pattern of the thus illuminated reticle R onto a wafer W.

In the present embodiment, each of the first, second and third beam splitters 3, 4a and 4b is provided by a half mirror. Also, the optical elements disposed between the laser 11 and the optical integrator 22 provide a light dividing and incoherence-transformation optical system, like the first embodiment described hereinbefore.

FIGS. 6A-6E illustrate light intensity distributions upon the sectional planes A-D in FIG. 5 as well as upon the reticle R surface, on the optical path shown in FIG. 5.

Referring now to FIG. 7, if in the present embodiment a reference orientation is set in the section L of the laser light just emitted by the laser source 11, as illustrated, corresponding orientations of the light beams La1, La2, Lb1 and Lb2 impinging on the wedge-shaped prisms 8a1, 8a2, 8b1 and 8b2 are placed radially about a reference point P, as illustrated in FIG. 7, wherein the reference point P coincides with the optical axis of the condenser lens 23. Here, FIG. 7 shows the sections of the four light beams La1-Lb2 impinging on the first deflector 8, as viewed from the wafer W side.

As regards the four light beams La1-Lb2 impinging on the wedge-shaped prisms 8a1-8b2 of the first deflector 8, they have different optical paths from the first beam splitter 3 to the first deflector 8, having different optical path lengths. The components of the optical system 20 are set so that such a difference in optical path length becomes larger than the temporal coherence length 1 as determined by the wavelength range of the laser light from the

laser 11. In the present embodiment, with respect to the optical path length, the light beams La1-Lb2 satisfy the following relations:

Lb2 > La2 > Lb1 > La 1

Lb2 - La2 = La2 - Lb1 = Lb1 - La1 = 1

With this arrangement, the four light beams are transformed into mutually incoherent lights, such that when they are superposed one upon another on the light receiving surface of the optical integrator 22, substantially no interference occurs among them.

It is to be noted here that, in the present embodiment, the four light beams La1-Lb2 inputted to the first deflector 8 have energies of substantially the same strength.

When the number of beam splitters used is "2<i> - 1" (i = 2, 3, 4, . . . n) and the number of light beams to be provided by the division through the optical system 20 is "2<i> " (i = 2, 3, 4, ... n), each beam splitter may have a reflection factor and a transmission factor of about 50%, respectively. If a different number of beam splitters and/or a different number of light beams are used, it may be necessary to adjust the proportion of the reflection factor and the transmission factor of each beam splitter so as to ensure that the light beams inputted to the first deflector 8 may have uniform energy strength. In this case, as a matter of course, the first deflector 8 should be provided with wedge-shaped prisms of a number corresponding to the number of the divided light beams.

The excimer laser 11 used in the present embodiment as a light source has relatively small spatial coherency. However, since in this embodiment a band-narrowing element such as an etalon, prism or the like, is used to narrow the wavelength range (bandwidth) of the laser light extremely so as to reduce chromatic aberration to be produced by the projection lens system 24, the temporal coherency of the laser is large. Particularly, in the present embodiment, light of a center wavelength lambda = 248.4 nm and a wavelength range DELTA lambda = 0.003 nm, of the laser light produced by an excimer laser is used. As a result, the coherence length of each of the light beams La1, La2, Lb1 and Lb2 is relatively long.

In consideration thereof, by imparting a predetermined optical path difference to these light beams through the optical system 20, they are transformed into mutually incoherent light beams and, as a result, when they are superposed one upon another on the light receiving surface of the optical integrator 22, substantially no interference fringe is formed by the interference of these light beams.

Further, through the driving means 102, the wedge-shaped prism 21 (second deflector) is rotated about the optical axis Of an optical systems-comprising the condenser lens 23 and the projection lens system 24. By this, the optical paths for the four light beams La1-Lb2 passing through the second deflector 21 and impinging on the light receiving surface of the optical integrator 22 as well as their positions of incidence upon the light receiving surface of the optical integrator change with time. Particularly, the first and second deflectors (prisms 8 and 21) are arranged so as to assure that the light beams La1-Lb2 always partially overlap one upon another, on the light receiving

surface of the optical integrator 22.

As shown in FIG. 6A, the laser light from the laser 11 has a sectional intensity distribution which is in the form of or similar to a Gaussian distribution. Therefore, the light beams La1-Lb2 inputted to the first deflector 8 each has a sectional intensity distribution like a Gaussian distribution, such as shown in FIG. 2B. When these light beams La1-Lb2 are inputted to and superposed one upon another on the light receiving surface of the optical integrator 22, the combined light provides a sectional intensity distribution which, as shown in FIG. 6C, is symmetrical with respect to the optical axis and, additionally, is substantially uniform. This is the effect of partial overlapping of the light beams La1-Lb2 on the light receiving surface of the optical integrator 22, as described hereinbefore. Further, in the neighborhood of the light emitting surface of the optical integrator 22 (i.e. in the sectional plane D), there is produced a light intensity distribution in such a form as shown in FIG. 6D. It is to be noted here that preferably the light beams La1-Lb2 are so superposed one upon another on the light receiving surface of the optical integrator that, even if in the sectional plane B each light beam has a sectional intensity distribution in a form other than the Gaussian distribution, these light beams still provide a uniform intensity distribution on the light receiving surface (plane C) of the optical integrator 22.

As described with reference to FIG. 7, the present embodiment is arranged so that the orientations of the four light beams La1-Lb2 in their sections are placed on the first deflector 8, radially about the reference point P. Further, in this arrangement, if the laser beam just emitted from the laser 11 (as denoted at L in FIG. 7) displaces in the direction of the arrow (upward as viewed in FIG. 7), the four light beams La1-Lb2 displace toward the reference point P, as seen from the orientations suggested by the arrows and small circles assigned to these light beams La1-Lb2, in FIG. 7. Accordingly, when the optical member 2 comprising a parallel surface plate is tilted by the driving means 101 relative to the optical axis so as to shift or translate the laser beam L, on the optical integrator 22 the four light beams La1-Lb2 displace toward or away from the center or reference point P to thereby change the size of the light flux, as a whole, impinging on the optical integrator 22. By changing the size in this manner, it is possible to change the size of the secondary light source surface as formed in the neighborhood of the light emitting surface of the optical integrator 22. This ensures that the G value of an illumination system (i.e. the reticle side numerical aperture (NA) of the system above the reticle, or the reticle side numerical aperture (NA) of the projection lens system) is changed without changing the non-uniformness in illuminance or without reducing the efficiency. Also, this ensures that, through the driving means 101, the G value of the illumination system is changed in different ways in accordance with the exposure conditions such as the type of resist applied to the wafer, the linewidth of the circuit pattern of the reticle R and the like, such that the exposure can be performed under optimum conditions.

Further, because of the inward orientation of the arrows of the four light beams La1-Lb2 as illustrated in FIG. 7, when these light beams are superposed the beam profile can be flattened, and therefore, reduction of non-uniformness in illuminance is ensured effectively.

The uniformness in illuminance distribution upon the reticle R surface is proportional to the uniformness in light intensity distribution on the light receiving surface of the optical integrator 22 and the number of the lens

elements constituting the optical integrator 22. On the other hand, when a plurality of coherent light beams such as the light beams La1, La2, Lb1 and Lb2 are inputted to an optical integrator, the larger the number of lens elements to which a single light beam is inputted, the larger is the number of mutually coherent secondary light sources formed in the neighborhood of the light emitting end of the optical integrator. Mutually coherent light beams from these secondary light sources easily interfere with each other to form an interference fringe of high contrast on the surface of a reticle. Since the optical integrator has a function for dividing the wavefront of a received light beam, the contrast of such an interference fringe is determined by the degree of spatial coherency of the laser.

In the present embodiment, as the laser 11, a laser having small spatial coherency is used and, in place of increasing the number of lens elements of the optical integrator 22, the optical arrangement is structured so that some lens elements receive all the light beams La1, La2, Lb1 and Lb2 to thereby increase the number of formed secondary light sources, to thereby avoid that an interference fringe, if any, formed on the reticle R damages the uniformness in illuminance distribution upon the reticle R. Further, since the light beams La1, La2, Lb1 and Lb2 are projected to the optical integrator 22 in different directions, interference fringes of low contrast, if any, formed by the light beams La1-Lb2 on the reticle R surface, have different phases. This results in a smoothing affect on the light intensity distribution as determined by these interference fringes, and therefore, the formation of interference fringes does not so influence the illuminance distribution on the reticle R surface.

Further, in the present embodiment, the wedge prism 21 is rotated to thereby shift the paths for the light beams La1-Lb2 impinging on the optical integrator 22 as well as their positions of incidence upon the optical integrator. Accordingly, the light intensity distribution to be formed on the light receiving surface of the optical integrator 22 has such a shape as formed by superposing plural light intensity distributions formed successively. This attains further enhancement of uniformness. Also, in the neighborhood of the light emitting surface of the optical integrator, the light beams LB1 and LB2 provide a distribution of secondary light sources (i.e. an effective light source) which changes with time. Accordingly, the number of secondary light sources increases substantially.

Since the excimer laser 11 is a pulsed laser, it emits pulsed laser light at preset time intervals. Where the number of laser pulses necessary for printing, by exposure, the circuit pattern of the reticle R onto the resist layer of the wafer W is denoted by M, if during the exposure the wedge prism 21 is rotated continuously, the light intensity distribution on the light receiving surface of the optical integrator 22 has such a shape as formed by superposing light intensity distributions of a number M, one upon another. Further, if the light beams La1-Lb2 produce secondary light sources of a number N per one laser pulse, then the wafer W is exposed with the lights from the secondary light sources of a number "M x N".

Next, the optical arrangement following the optical integrator 22 will be explained in detail.

The condenser lens 23 comprises a lens assembly constituted by plural lens elements disposed along the optical axis, and it serves to direct, toward the reticle R, the light beams from a large number of secondary light sources as

formed in the neighborhood of the light emitting surface of the optical integrator 22. The secondary light sources of a large number are distributed in a plane perpendicular to the optical axis of the condenser lens 23, and the spacing between this plane (secondary light source forming plane) and the light entrance side (front) principal plane of the condenser lens 23 is equal to the focal length of the condenser lens 23. On the other hand, the spacing between the light exit side (rear) principal plane of the condenser lens 23 and the reticle R is set to be equal to the focal length of the condenser lens 23. In this structure, each of the light beams from the secondary light sources of a large number, is transformed by the condenser lens 23 into parallel light, and the resultant parallel light beams are efficiently superposed one upon another on the reticle R surface. The illuminance distribution on the reticle R at this time is satisfactorily uniform, as illustrated in FIG. 6E.

Similarly, the projection lens system 24 comprises a lens assembly constituted by plural lens elements disposed along the optical axis, and it serves to bring the circuit pattern surface of the reticle R and the surface of the wafer W to be exposed, into an optically conjugate relationship. In the present embodiment, the structure is arranged so that the projection lens system 24 forms an image of the circuit pattern of the reticle R on the wafer W at a reducing magnification of 1:5. The projection lens system 24 has an entrance pupil (not shown) which is placed in an optically conjugate relationship with the secondary light source forming plane adjacent to the light emitting surface of the optical integrator 22. Thus, like the reticle R, the wafer W is illuminated in the manner of Kohler illumination.

The optical integrator 22 and the condenser lens 23 is arranged so as to bring the light receiving surface of the optical integrator 22 and the circuit pattern surface of the reticle R into an optically conjugate relationship.

As described in the foregoing, the illumination device of the present embodiment uses as a light source an excimer laser (11) having small spatial coherency and, through the optical system 20, mutually incoherent light beams La1-Lb2 are inputted to the light receiving surface of the optical integrator 22 along different directions so that they are superposed partially one upon another. With this arrangement, quite a large number of secondary light sources can be formed in the neighborhood of the light emitting surface of the optical integrator 22 and, additionally, the intensity distribution on the light receiving surface of the optical integrator 22 can be made uniform. As a result, it is possible to provide an effective light source having closely distributed secondary light sources, and therefore, it is possible to illuminate the circuit pattern surface of the reticle R in the manner best suited for correct and accurate transfer of the circuit pattern of the reticle to the wafer, such that an image of the circuit pattern of the reticle R can be correctly and accurately printed on the wafer W.

The rotatable wedge prism 21 may be provided between the optical integrator 22 and the reticle R. Also, if in the optical path within the optical system 20 the diffraction loss of the light beams La1-Lb2 is large, an imaging system such as a focal converter may be provided on the optical path so as to assure efficient transmission of the light beams La1-Lb2 to the optical integrator 22. On that occasion, such an imaging system may be disposed so as to provide an optically conjugate relationship between the surfaces of predetermined optical elements, of the optical system 20, through which the light passes.

While in the present invention a light beam from a coherent light source such as a laser is amplitude-divided to provide a plurality of light beams, the number of such light beams is preferably about three (3) to twenty (20). By using light beams of a number within such a range, the optical system can be made relatively compact and, additionally, a satisfactory effective light source is obtainable.

Further, in the present invention, it is effective to use such a laser as having a large number of transverse modes and small spatial coherency and, particularly, good results are obtainable by using a laser (particularly an excimer laser) having a transverse mode of a number not less than one hundred (100). When an illumination device using such a laser as a light source is incorporated into a reduction projection type exposure apparatus, as in the FIG. 5 embodiment, it is possible to provide an exposure system having good pattern transfer performance.

While in the present embodiment the first deflector 8 comprises transmission type wedge-shaped prisms, it may be provided by a plurality of mirrors disposed to be associated with corresponding light beams. On such an occasion, a driving means operable to controllably drive these mirrors independently of each other may be used, such that the first deflector may have a function of a scanner.

In accordance with some embodiments described hereinbefore, it is possible to provide an illumination device having advantageous features such as follows:

(a) Not only is a uniform illuminance distribution provided on a surface, to be illuminated, such as the surface of a reticle or wafer, but also an effective light source comprising a large number of distributed secondary light sources can be formed in the optical path of the illumination device. Accordingly, the surface to be illuminated can be illuminated satisfactorily. As a result, when the illumination device of the present invention is used to illuminate a reticle and a wafer, it is possible to transfer the circuit pattern of the reticle onto the wafer correctly and accurately.

(b) By inverting the light beams with respect to their sections and by superposing them one upon another, even if the light from a light source has an asymmetrical intensity distribution, it is possible to form a light flux having an intensity distribution symmetrical with respect to the optical axis and to reduce the non-uniformness in illuminance on the surface to be illuminated.

(c) By placing plural divided light beams so that their orientations in their sections are set radially toward a center (optical axis), only a displacement of the light from the light source in a predetermined direction can change the sigma value of the illumination system.

FIG. 8 is a schematic view showing a general structure of an illumination device according to a further embodiment of the present invention. The device of the present embodiment is applicable to a semiconductor device manufacturing exposure apparatus such as shown in FIG. 1, but clearly it is also applicable to other types of systems.

In the present embodiment, a laser beam emitted by a KrF excimer laser 11 and having an asymmetrical sectional intensity distribution is inputted to a beam expanding optical system 81 by which the diameter of the laser beam is expanded. Then, the laser beam passes through a prism 113 and enters a first beam

reversing system 31 which comprises a parallel flat plate 83, a mirror 12, a phase shift plate 111 and another mirror 13, which mirror has a beam inverting function. Thereafter, it goes through a quarter waveplate 16 and then enters a second beam reversing system 32 of a similar structure as the first beam reversing system 31. Then, the laser beam is reflected by a mirror 82 and is inputted to an optical integrator 22. Laser beams from lens elements of the optical integrator 22 are collected by a condenser lens 23 and inputted to a scanner comprising a rotatable wedge-shaped prism 21. The light from the prism 21 is directed to a surface to be illuminated, such as, for example, the surface of a reticle (not shown), whereby the reticle surface is illuminated with uniform illuminance.

Features of the components of the illumination device according to the present embodiment will be explained below.

FIG. 9A illustrates the function of the first beam reversing system shown in FIG. 8. Since the phase shift plate 111 as illustrated in FIG. 8 may be used as desired, it may be omitted and is not illustrated in FIG. 9A and in FIGS. 9B and 9C.

Generally, a laser beam has certain polarization characteristics. For this reason, by passing a laser beam from a laser source through an optical member such as a phase plate, a Fresnel rhombus or the like, it is possible to transform the laser beam into one having a random or a specific direction of polarization as can be represented by circularly polarized light.

In the embodiment shown in FIG. 9A, the laser beam L is inputted to a parallel flat plate 83 at a predetermined angle. In the FIG. 9 embodiment, the parallel flat plate 83 has its surface 83a covered by a multi-layered film, such that, when the laser beam L is inputted thereto at a predetermined angle, it serves to provide a reflection light of an S-polarized laser beam and a transmission light of a P-polarized laser beam. Namely, the parallel flat plate 83 functions as a polarization beam splitter. The P-polarized laser beam transmitted through the surface 83a goes through the backside surface 83b of the parallel flat plate 83, covered by an anti-reflection film, substantially without a loss of light quantity. Subsequently, the thus transmitted laser beam reflected by two mirrors 12 and 13 in this order, whereby it is returns to the backside surface 83b of the parallel flat plate 83, to ensure that the center of the returning laser beam coincides, at a position 83c, with the center of the S-polarized laser beam produced by the reflection of the supplied laser beam L by the parallel flat plate 83 and also that the returning laser beam is propagated in the same direction as the S-polarized laser beam. Since the returning laser beam is still a P-polarized laser beam as it passes through the parallel flat plate 83, due to the effect of the anti-reflection film, there is substantially no loss of light quantity attributable to the surface reflection. Accordingly, there is only a small loss of light quantity in the P-polarized laser light, caused by the two mirrors 12 and 13.

In the beam reversing system 31 shown in FIGS. 9A through 9C the angle of incidence of the laser beam to each of the optical members 83, 12 and 13 is fixed and, additionally, these optical members can be prepared only in relation to a single wavelength. Accordingly, by using a multi-layered film, it is possible to reduce the loss of light quantity to an order which can be disregarded without inconveniences. As a result, in the present embodiment, it is possible to divide a laser beam inputted to the reversing system 31 into

two laser beams having different polarization components and then to re-combine the divided laser beams and direct those beams toward the second beam reversing system 32, substantially without loss of light quantity.

In the present embodiment, particular note should be paid to three features such as follows:

(I) Two laser beams of different polarization components have directions of polarization which are perpendicular to each other.

(II) It is easy to provide an optical path difference, between the two laser beams of the two polarization components, of a length not less than the coherence length of the laser light.

(III) By the inversion through the mirror, the S-polarized laser beam and the P-polarized laser beam have mutually inverted light intensity distributions.

Of these features, features (I) and (II) are contributable to the prevention of interference between the laser beam of the two polarization components.

The orthogonal relationship of the directions of polarization, in feature (I), is important not only in alleviating the interference condition, but also in assuring the matching with a following optical system. Also, it is preferable to adjust the optical arrangement in preparation, in accordance with the state of polarization of the laser beam to be inputted to the reversing system, in order to ensure that the ratio in intensity of the two polarized laser beams emanating from the reversing system 31 is maintained at 1:1.

The optical path difference of the laser beams in feature (II) is an important condition necessary for preventing the interference. Where the half width of the emission spectrum of the laser 11 is denoted by DELTA lambda and the center wavelength is denoted by lambda 0, the coherence length can be expressed by " lambda 0<2> / DELTA lambda ". Also, in an aspect of avoiding weak high order interference terms to be produced in dependence upon the period of laser cavity length as of a He-Ne laser or the like, the combination with feature (I) is effective.

Feature (III) is for the shaping of the intensity distribution of the laser light. This is represented in FIG. 9A by the exchange between the laser beam L2 depicted by a dash-and-dot line and the laser light L3 depicted by a chain line. By passing the laser beams through the optical components illustrated in the drawing, the P-polarized laser beam is inverted relative to the S-polarized laser beam and, by this, the degree of symmetry in the sectional intensity distribution of the laser light L in the sheet of the drawing is enhanced.

FIGS. 9B and 9C are schematic views, respectively, each showing a major portion of another example of the beam reversing system 31.

In the beam reversing system 31 of the FIG. 9B example, the components of the beam reversing system of the FIG. 9A embodiment are replaced by a single prism block 14. When the prism block 14 is arranged so that the laser beam is internally reflected by the prism block by an even number of times, an S-polarized laser beam directly reflected by the surface 14a of the prism block 14 and a P-polarized laser beam as reflected by the inside reflection surfaces 14b and 14c of the prism block 14 can be superposed upon another in the manner

compensating the asymmetric intensity distribution of the input laser beam L.

FIG. 9C shows an example of a beam reversing system 31 which is of a combined form of the FIG. 9A example and the FIG. 9B example.

Generally, when the direction of polarization of a laser beam inputted to a polarization beam splitting surface is isotropic (random), the laser beam may be inputted directly. When a rectilinearly polarized laser beam is used, a quarter waveplate may be inserted into the optical path so as to provide isotropic polarization. Alternatively, the direction of polarization of the laser beam to be inputted may be set at an angle of 45 degrees with respect to the polarization beam splitting surface, so as to assure that S-polarized light and P-polarized light have an intensity ratio of 1:1. By doing so, in the examples of FIGS. 9A-9C, it is possible to assure that two laser beams of different polarization components emanating from the beam reversing system 31 have an intensity ratio of 1:1.

In the beam reversing systems 31 of the examples shown in FIGS. 9A-9C, by the inversion, the degree of symmetry of the intensity distribution of the laser beam only with respect to one direction is improved. In order to enhance the degree of symmetry of the laser beam as a whole, it may be necessary to improve the degree of symmetry with respect to another direction.

FIG. 10 is a schematic view of an embodiment wherein the beam reversing system 31 (first beam reversing system) of the FIG. 9A example is combined with a similar beam reversing system 32 (second beam reversing system), the second beam reversing system being coupled in a direction perpendicular to the first beam reversing system 31.

In the FIG. 10 example, the first and second beam reversing systems 31 and 32 are effective to attain inversion in two orthogonal directions, by which the degree of symmetry of the intensity distribution of the laser beam as a whole can be improved.

When the optical path difference of the two laser beams produced by the first beam reversing system 31 is denoted by OPD1 and the optical path difference of the two laser beams produced by the second beam reversing system 32 is denoted by OPD2, the light flux emanating from the second beam reversing system 32 contains four, first to fourth light beams. Assuming now that the first light beam is such a beam having been reflected by the parallel flat plate 83 in each of the first and second beam reversing systems 31 and 32, the second light beam is such a beam having been transmitted through the parallel flat plate of the first reversing system 31 and having been reflected by the parallel flat plate of the second reversing system 32, wherein an optical path difference OPD1 is imparted to the second light beam, relative to the first light beam. Also, the third light beam is such a beam having been reflected by the parallel flat plate of the first reversing system 31 and having been transmitted through the parallel flat plate of the second reversing system 32, wherein an optical path difference OPD2 is imparted to the third light beam, relative to the first light beam. The fourth light beam is such a beam having been transmitted through the parallel flat plates of the first and second beam reversing systems, wherein an optical path difference of an amount "OPD1 + OPD2" is imparted to the fourth light beams, relative to the first light beam.

In order to avoid interference of these light beams, in the present embodiment, the optical path differences OPD1 and OPD2 are set to have a difference (length) which is greater than the coherence length of the laser light. In this particular example, the following relation is satisfied:

OPD2 = OPD1 x 2

If it is desired to use two beam reversing systems such as at 31 in FIGS. 9A, 9B or 9C so as to attain inversion the optical path in two orthogonal directions, particular attention should be paid to the direction of polarization. If the two reversing systems such as at 31 in FIGS. 9A-9C are directly coupled with each other, then the P-polarized light from the first beam reversing system 31 is transformed into an S-polarized light by the second beam reversing system 32, whereas the S-polarized light from the first beam reversing system 31 is transformed into a P-polarized light by the second beam reversing system 32. Accordingly, there are produced only two light beams, i.e., the first and fourth light beams in the case of the embodiment described hereinbefore. To avoid this, it is necessary to provide a quarter waveplate or some element equivalent to the quarter waveplate such as a Fresnel rhombus, for example, between the first and second beam reversing systems 31 and 32, so as to rotate the direction of polarization of the linear polarization components by 45 degrees. In the arrangement of FIG. 10, a quarter waveplate 16 is inserted.

Another example that uses the beam reversing system 31 of FIGS. 9A-9C is such that, without using a special polarization element such as a quarter waveplate or a half waveplate, the laser beam emanating from the first beam reversing system is inputted to another beam reversing system wherein the beam is reversed successively in a direction at an angle 45 degrees with respect to the reversing direction by the first reversing system. In this example, since the direction of polarization of the P-component and the S-component of the two light beams amplitude-divided by the first beam reversing system have an angle of 45 degrees with respect to a polarization beam splitting surface of the parallel flat plate of the second reversing system, the P-polarization component and the S-polarization component of the laser beams inputted to the parallel flat plate of the second reversing system are again split into P-polarized light and S-polarized light at an intensity ratio of 1:1. Of course, similar effects are attainable by inserting a quarter waveplate or a half waveplate.

By inverting the optical path successively four times, each by an angle of 45 degrees, the laser light is finally divided into coherent light beams of a number 2<4> = 16, which are incoherent with each other. Additionally, a beam profile having an excellent symmetry is totally obtained. As a matter of course, it is preferable that any pair of the sixteen (16) light beams have a mutual optical path difference greater than the coherence length. This can be easily accomplished by satisfying the following relation:

OPDn = OPD1 x 2<n - 1 >

where the optical path difference of the two light beams formed by the n-th beam reversing system is denoted by OPDn. However, it is to be noted that, if the optical path difference OPDn becomes so large, a smaller value may be selected from the relationship with the optical path difference OPD1 and the coherence length.

The beam splitting and combining method based on amplitude division of laser light, using a polarization beam splitting surface or the like, is basically a beam symmetrizing and shaping method with the least loss of light quantity. There does not occur a loss of light quantity at an edge portion, which otherwise might be caused by a conventional wavefront dividing method and the like. The loss of light quantity occurs only by a film formed on a mirror or a beam splitter. Also, since the total coherency of the laser light itself is made small, the formation of speckle is reduced sufficiently.

The foregoing is the basic principle of symmetrization of a sectional intensity distribution of a laser beam and incoherence transformation of a laser beam, in the present embodiment. When the present invention is applied to an exposure apparatus in which a laser such as an excimer laser, for example, is used as a light source, this is a case wherein slight modification of the structure of the beam reversing system provides better results.

As an example, as illustrated in FIG. 11, the beam reversing system 31 of FIGS. 9A-9C may be modified so that two laser beams 51 and 52 emanating from the parallel flat plate 83 have their emission angles slightly different from each other. When the two laser beams 51 and 52 have different emission angles, as in this example, gradually the laser beams separate from each other as they are propagated. As a result, if plural reversing systems are used in combination, a large deviation is produced between these light beams. On such an occasion, as illustrated in FIG. 12, preferably the beam reversing systems 31 and 32 may be coupled with the intervention of a relay system such as at 25 in FIG. 12.

When, in the reversing system 31 of FIG. 11, the point of intersection of the central ray of the two beams 51 and 52 with the surface 11a of the parallel flat plate 11 is denoted by 17a and a similar point of intersection in the next reversing system is denoted by 17b, then it is preferable that the relay system 25 has a structure such as shown in FIG. 13. Since the points 17a and 17b are in an optically conjugate relationship, one role of the relay system 25 is to ensure the imaging relation as depicted by chain lines.

On the other hand, since the laser light propagated through each reversing system comprises parallel light, actually it is once focused as depicted by solid lines and, thereafter, it is transformed back into parallel light. The problem to be considered here is the presence of the convergent point 18. When an excimer laser is used as a light source, since the excimer laser produces a laser beam of very high intensity, if the excimer laser beam is converged in air, at such a convergent point there occurs a concentration of electric field which may result in dielectric breakdown of the air and thus in production of a spark in the air. In consideration thereof, in the relay system 25 of the FIG. 13 example, a vacuum chamber 21 is provided on the optical path between relay lenses 19a and 19b so that the convergent point 18 is placed in the chamber 21. Thus, through windows 20 of the vacuum chamber 21, the laser light is directed to the next reversing system. Since in this arrangement the convergent point of the laser beam is kept in a vacuum, the device can be free from a non-linear absorption phenomenon.

FIG. 13 shows a basic structure of the relay system 25 and, when such a relay system is incorporated into a device having two reversing systems 31a (FIG. 11) disposed with relative rotation by an angle of 90 degrees, a quarter waveplate may be placed in a portion of the optical path of the relay system 25.

In the present embodiment, the beam profile of the laser light is improved and, additionally, the coherency of the laser light is reduced, in the manner as described hereinbefore and, finally, the thus obtained laser light is inputted to an optical integrator 22 such as shown in FIG. 8.

If, on this occasion, the beam reversing system used produces a difference in the angle of emission between the two divided laser beams, as shown in FIG. 11, a relay system may be provided so as to assure that the center of the optical integrator 22 as a whole coincides with a position which is optically conjugate with the point 17a. If the reversing system used does not produce a difference in the angle of emission between the two divided laser beams, the structure is set to assure that the center of the light beam coincides with the center of the optical integrator 22 as a whole.

Another important feature of the present embodiment resides in the reduction of the interference fringe which is inevitably produced by an optical integrator. While the interference fringe can be reduced in some ways, one method is to superpose different interference fringes upon one another to reduce or cancel these interference fringes totally, by using an averaging effect. The embodiment having been described with reference to FIG. 5 and using a scanner, is based on this method and is arranged to execute such a superposition of interference fringes with respect to time. From a practical standpoint, it is desirable to add the removal of temporal coherency to this. Although removal of temporal coherency is provided by using the reversing optical system, as a result of passage through the optical integrator 22 each laser beam produces on the reticle surface an interference fringe as determined by the pitch of arrayed lens elements constituting the optical integrator 22.

In the foregoing description, the reversing system is arranged to superpose two laser beams one upon another. With regard to those paired laser beams, except for the point that an optical path difference is provided by the division, they are common in that they pass through the same optical element. For this reason, the interference fringes as formed by these two laser beams on the reticle surface are analogous. Thus, relative shifting of the phases of the two interference fringes formed on the reticle by the two light beams, by a half pitch, so that the two light beams are superposed one upon another in a manner compensative with each other, is very advantageous with respect to the uniformness of illuminance distribution. As described hereinbefore, the two laser beams superposed one upon another are incoherent with each other in duplicate condition, i.e., in the point that there is an optical path difference and in the point that their polarization directions are orthogonal to each other. Accordingly, the two interference fringes are superposed one upon another in incoherent relationship.

If the intensity distribution of a laser beam outputted from a laser has a profile of a low degree of symmetry, as shown in FIG. 14 the reversing system 31 of FIGS. 9A through 9C may be used in duplication such that, after symmetrization of the beam profile, the beam may be inverted for the incoherence transformation. To this end, the reversing system of FIG. 9A or the reversing system of FIG. 11 may be used. Alternatively, both types may be used in combination. The phase of the interference fringe can be shifted in some ways. A first method is that plural laser beams are inputted to an optical integrator with inclination and in different directions, so that the interference fringes by these laser beams are superposed one upon another with mutual positional deviation whereby the interference fringes are cancelled totally. FIG. 15 is a

schematic view for explaining the manner of removal of interference fringes, based on inclined light input according to the first method. For convenience in explanation, FIG. 15 illustrates a case wherein two light beams are inputted in two different directions to small lenses 22a and 22b of an optical integrator 22. The illumination system in this illustrated example has a simple structure, and light beams emanating from the lenses 22a and 22b pass through a condenser lens 23 and illuminate the surface of a reticle R. The interference fringe as formed on the reticle R surface by a first light beam from the lens 22a is depicted by a solid line 6a, while the interference fringe as formed by a second light beam from the lens 22b is depicted by a broken line 6b. As illustrated, these interference fringes 6a and 6b are mutually compensative, with the peaks and troughs of one of the solid line 6a and the broken line 6b being superposed on the troughs and peaks of the other. As a result, a totally uniform illuminance distribution can be produced on the reticle R surface and, therefore, such a uniform illuminance distribution can be produced on the surface of a wafer which is optically equivalent to the reticle surface.

The difference in the angle of incidence between the light beams, as in this example, can be produced by a beam reversing system such as at 31 in FIG. 11. Accordingly, the angular difference of the two beams to be provided by the beam reversing system is so set that the peaks and troughs of a pair of interference fringes are in a compensative or complementary relationship, on the surface to be illuminated. Since the pitch of an interference fringe can be calculated on the basis of the size of each of small lenses of the optical integrator (fly's-eye lens), the structure of the condenser lens and the like, the angular difference to be produced can be predetected by calculation.

With reference to FIG. 15, one-dimensional expansion has been considered. Actually, however, the reticle R surface has two-dimensional expansion. For this reason, it is desirable that the angular deviation is produced with respect to at least two directions, namely, orthogonal X and Y directions. To this end, as shown in FIG. 12, plural reversing systems may be used in combination.

A second method is to produce a phase distribution on the light receiving surface of the optical integrator. FIG. 16 is a schematic representation for explaining this method. The basic structure of the illumination system is similar to that of the illumination system shown in FIG. 15. In this example, however, plural laser beams are inputted to small lenses 22a and 22b at the same angle. Here, the first and second light beams have a difference with respect to the phase distribution as formed by the first light beam at the light receiving surface 22c of the small lenses 22a and 22b and the phase distribution as formed by the second light beam at the light receiving surface 22c. If the first light beam has a uniform phase distribution at the light receiving surface 22c of the small lenses 22a and 22b, as illustrated in FIG. 16, the second light beam has such a phase distribution wherein the phase is shifted by 180 degrees from the boundary between the small lenses 22a and 22b. Considering with reference to the center A on the reticle R surface, if the interference fringes as formed by the light beams from the small lenses 22a and 22 b, based on the first light beam, are in a mutually intensifying condition, then the interference fringes as formed by the light beams from the small lenses 22a and 22b, based on the second light beam, are in a mutually attenuating condition, since the phase of one of the interfering lights is shifted relative to the other by 180 degrees. Accordingly, the phases of the interference fringes by the first and second light beams are in a compensative or complementary relationship, such that when they are superposed one upon another, the uniformness of light on the reticle

R surface and, thus, on the wafer surface can be improved significantly.

Such a shift of the phase to the wavefront of a light by 180 degrees can be accomplished by inserting a phase difference applying member having a film formed by evaporation or the like, effective to shift the phase, into a module of incoherence transformation system such as shown in FIGS. 9A-9C.

FIGS. 17A-17C are schematic views, respectively, each showing a reversing system 31 having such a phase difference applying means 111.

FIGS. 17A and 17B each shows an example wherein a phase shift plate 111 (phase difference applying means) is inserted into the reversing system of the FIG. 9A example. If the intensity distribution of a supplied laser beam is sufficiently symmetric so that the reversing system of FIG. 9A provides the function of symmetrization and also the function of such a phase shift plate 111, the structure as illustrated in FIG. 17A or 17B is a basic form for producing complementary interference fringes with the phase distribution. If the profile of the intensity distribution of the laser beam is not good so that the reversing system cannot provide both the symmetrizing function and the phase shifting function, the phase shift plate 111 may be inserted into the second beam reversing system of FIG. 14 to provide a basic unit of the structure such as shown in FIG. 18.

In FIGS. 17A and 17B, as an example, the phase shift plate 111 may be manufactured by forming a surface height difference (112a, 112b) on a parallel flat plate 112 (see FIG. 19A) by using a film structure (hatched portion) formed by evaporation. In FIG. 19A, both faces of the parallel flat plate are covered by anti-reflection films. At the lower part 112b of the left-hand phase, an additional film is provided on the anti-reflection film, with a thickness d = lambda /[2(n - 1)], wherein n is the refractive index of the film and lambda is the wavelength of the used light. Thus, the light passing through the upper part 112a and the light passing through the lower part 112b have a phase difference of 180 degrees. In place of providing a phase difference through a film, as shown in FIG. 19B, a part of a parallel flat plate 112 may be removed by etching to produce a phase difference of 180 degrees (i.e., a half wavelength), and an anti-reflection film may be formed thereon.

FIG. 17C shows an example wherein a prism block 15 constituting a beam reversing system is directly equipped with such a phase imparting means. The incoherence transformation unit as shown in FIGS. 17A-17C is provided by two-dimensionally combining the phase shifting boundary so as to suppress two-dimensionally the production of interference fringes, like the first method. For example, when the reversing system 31 of FIGS. 17A-17C is to be used in duplication, like the FIG. 10 example, one phase shift plate 111 is inserted into each reversing system. Here, it is desirable that the first and second phase shift plates are so set that their boundaries are placed in an equivalently orthogonal relationship. Further, while it depends on the structure of the lens array of the optical integrator, it is desirable that their equivalently intersecting point is in the neighborhood of the center of the optical integrator as a whole. On that occasion, it is further desirable that the boundary line is in the co-directional relationship with the array of the lens elements of the optical integrator.

The boundary of the phase shift plate is not limited to the FIG. 19A example or the FIG. 19B example, wherein it is defined by a line. As an example, it

may be defined by a group of straight lines following the boundaries of the constituent elements of the optical integrator. Various modifications are possible, other than this.

FIG. 8 shows one representative embodiment, wherein a phase shift plate such as at 111 in FIG. 17A is used and wherein two stages of beam reversing systems 31 and 32 are used to direct the light to an optical integrator 3. Further, in the device of FIG. 8, in preparation for a possible difficulty in removing an interference fringe or speckle in accordance with the phase shift method, a scanner 21 is provided. If the required uniformness in the illuminance distribution is not so high, the scanner 21 may be omitted. Further, the system may be used in the manner that with regard to the X direction the phase shift plate 111 is used while, on the other hand, with regard to the Y direction perpendicular to the X direction, the angle shifting method is used.

When plural beam reversing systems are used in combination for the incoherence transformation, if a relay system such as at 25 in FIG. 13 is used as required, the combined use of these components in any manner can accomplish the object of the present invention.

The relay system 25 of FIG. 13 is particularly effective on an occasion when two light beams have a difference in the angle of emission or on an occasion when the phase shift plate 111 is used.

If the boundary of the phase shift plate sufficiently corresponds to the boundary of the individual small lenses which are the constituent elements of the optical integrator 22, without use of the relay lens 25 in FIG. 13, then use of such a relay lens is not necessary. Further, for imparting an optical path difference to the light beams for the incoherence transformation, the following relation is satisfied in the foregoing embodiments:

OPDn = OPD1 x 2<n - 1 >

However, it is possible that, while taking the optical path difference OPD1 as a maximum, the arrangement may be set to satisfy the following relation:

OPDn = OPD 1/2 <n - 1 >

In such a case, the optical path difference OPDn should be made longer than the coherence length. Further, the value "2<n - 1> " may be replaced by "3<n - 1> " or any one of other values, provided that the optical path difference between mating light beams is greater than the coherence length.

In accordance with some embodiments of the present invention, light from a high-coherency light source such as a laser, for example, is passed through a reversing system or systems of the structure described above, and by this, incoherence-transformation of the light is attained. Also, the asymmetry of the intensity distribution of the laser beam itself can be corrected. Further, in the case of a pulsed laser such as an excimer laser, both the correction of non-uniformness in intensity distribution and the correction of interference fringe can be performed to each individual pulses from the excimer laser. As a result, the uniformness in illuminance distribution on the surface being illuminated can be improved significantly.

While the invention has been described with reference to the structures disclosed herein, it is not confined to the details set forth and this application is intended to cover such modifications or changes as may come within the purposes of the improvements or the scope of the following claims.

CLAIMS: What is claimed is:

[*1] 1. An exposure apparatus comprising:

a light source for producing light for transferring a pattern of an original onto a substrate;

a light dividing optical system for dividing light from said light source into a plurality of light beams;

an illumination optical system including an optical integrator, said optical integrator receiving the plurality of light beams and defining a plurality of secondary light sources to illuminate the substrate; and

changing means for changing the position of incidence of each of the plurality of light beams on said optical integrator, said changing means shifting the position of incidence of each of the light beams toward or away from the center of said optical integrator.

[*2] 2. An apparatus according to claim 1, wherein said changing means comprises an optical member disposed on a path of the light from said light source, between said light source and said optical integrator.

[*3] 3. An apparatus according to claim 2, wherein said optical member shifts the light from said light source, relative to an axis of the path of the light.

[*4] 4. An apparatus according to claim 1, wherein said light dividing optical system comprises means for projecting the light beams on said optical integrator, in different directions.

[*5] 5. An apparatus according to claim 1, wherein said light dividing optical system divides the light from said light source into at least four light beams, and wherein the at least four light beams are projected on said optical integrator to surround the center of said optical integrator.

[*6] 6. An apparatus according to claim 5, wherein the at least four light beams are grouped into plural sets, and wherein the light beams in each set are shiftable substantially symmetrically with respect to the center of said optical integrator.

[*7] 7. An apparatus according to claim 1, wherein the light beams are shiftable substantially in opposite directions, on said Optical integrator.

[*8] 8. An apparatus according to claim 1, wherein said light source comprises an excimer laser, and wherein said light dividing optical system imparts at least one optical path difference in the light beams.

[*9] 9. An exposure method comprising the steps of:

dividing light from a light source into a plurality of light beams;

projecting the plurality of beams onto an optical integrator to define a plurality of light sources by the optical integrator;

changing the position of incidence of each of the plurality of light beams upon the optical integrator, toward or away from the center of the optical integrator; and

illuminating, after said changing step, an original with the plurality of light sources defined by the optical integrator, to transfer a pattern of the original onto a substrate.

[*10] 10. A method according to claim 9, wherein said changing step comprises (i) using an optical member disposed on a path of the light from the light source, between the light source and the optical integrator, and (ii) shifting the light from the light source by the optical member, relative to an axis of the light path.

[*11] 11. A method according to claim 9, further comprising projecting the light beams on the optical integrator, in different directions.

[*12] 12. A method according to claim 9, further comprising dividing the light from the light source into at least four light beams, and projecting the at least four light beams on the optical integrator to surround the center of the optical integrator.

[*13] 13. A method according to claim 12, further comprising grouping the at least four light beams into plural sets, and shifting the light beams in each set substantially symmetrically with respect to the optical integrator.

[*14] 14. A method according to claim 9, further comprising shifting the light beams substantially in opposite directions, on the optical integrator.

[*15] 15. A method according to claim 9, further comprising using an excimer laser as the light source, and imparting at least one optical path difference in the light beams.

[*16] 16. A semiconductor device manufacturing method comprising the steps of:

dividing light from a light source into a plurality of light beams;

projecting the plurality of light beams onto an optical integrator to define a plurality of secondary light sources;

changing the position of incidence of each of the plurality of light beams on the optical integrator, toward or away from the center of the optical integrator; and

illuminating, after said changing step, a mask with the plurality of secondary light sources defined by the optical integrator, to transfer a pattern of the mask onto a wafer.

[*17] 17. A method according to claim 16, wherein said changing step comprises (i) using an optical member disposed on a path of the light from the light source, between the light source and the optical integrator, and (ii) shifting the light from the light source by the optical member, relative to an axis of the light path.

[*18] 18. A method according to claim 16, further comprising projecting the light beam on the optical integrator, in different directions.

[*19] 19. A method according to claim 16, further comprising dividing the light from the light source into at least four light beams, and projecting the at least four light beams on the optical integrator to surround the center of the optical integrator.

[*20] 20. A method according to claim 19, further comprising grouping the at least four light beams into plural sets, and shifting the light beams in each set substantially symmetrically with respect to the optical integrator.

[*21] 21. A method according to claim 16, further comprising shifting the light beams substantially in opposite directions, on the optical integrator.

[*22] 22. A method according to claim 16, further comprising using an excimer laser as the light source, and imparting at least one optical path difference to the light beams.

[*23] 23. An apparatus according to claim 1, further comprising means for imaging a pattern of the original, illuminated with the plurality of secondary light sources, upon the substrate.

[*24] 24. A method according to claim 9, further comprising imaging the pattern of the original, illuminated with the plurality of secondary light sources, upon the substrate, to transfer the pattern of the original onto the substrate.

[*25] 25. A method according to claim 16, further comprising imaging the device pattern of the mask illuminated with the plurality of secondary light sources, upon the wafer, to transfer the pattern of the mask onto the wafer.

[*26] 26. An exposure apparatus comprising:

means for providing a plurality of light beams;

an illumination optical system including an optical integrator, said optical integrator receiving the plurality of light beams to define a plurality of secondary light sources for exposing a substrate; and

changing means for changing the position of incidence of each of the plurality of light beams upon said optical integrator, said changing means shifting the position of incidence of each beam toward or away from the center of said optical integrator.

[*27] 27. An apparatus according to claim 26, further comprising means for imaging a pattern of an original, illuminated with the plurality of secondary light sources, upon the substrate.

[*28] 28. A device manufacturing method, for use with an optical integrator, comprising the steps of:

changing the position of incidence of each of a plurality of light beams upon the optical integrator, toward or away from the center of the optical integrator, to define a plurality of secondary light sources by the optical integrator;

transferring, after said changing step, a device pattern onto a substrate with the plurality of secondary light sources defined by the optical integrator.

[*29] 29. A method according to claim 28, wherein said transferring step comprises imaging the device pattern, illuminated with the plurality of secondary light sources, upon the substrate.

[*30] 30. An exposure apparatus for exposing a substrate to a mask pattern, said apparatus comprising:

a light source for producing light;

an optical integrator for forming a plurality of secondary light sources with light from said light source;

an irradiating optical system for irradiating said optical integrator with the light from said light source, said irradiating optical system comprising first optical means for converting the light from said light source into an off-axis light beam having an optical path deviated from an optical axis of said irradiating optical system, and second optical means for changing a position of incidence of each ray of the off-axis light beam on the optical integrator, toward or away from a center of said optical integrator; and

a directing optical system for directing light beams from the secondary light sources, formed by said optical integrator, onto the mask pattern.

[*31] 31. An apparatus according to claim 30, wherein said first optical means comprises a plurality of beam splitters and a plurality of bending mirrors.

[*32] 32. An apparatus according to claim 30, wherein the off-axis light beam consists of four light beams.

[*33] 33. An apparatus according to claim 30, wherein said light source comprises an excimer laser.

[*34] 34. An apparatus according to claim 30, further comprising a projection optical system for projecting an image of the mask pattern onto the substrate.

[*35] 35. An exposure apparatus for exposing a substrate to a mask pattern, said apparatus comprising:

secondary light source forming means for forming a plurality of secondary light sources;

irradiating means for irradiating said secondary light source forming means with light, said irradiating means comprising means for providing off-axis light having an optical path deviated from an optical axis of said irradiating means, wherein said irradiating means is arranged so that a position of incidence of each ray of the off-axis light upon said secondary light sources forming means is changeable, toward or away from a center of said secondary light source forming means; and

means for directing light beams from the secondary light sources onto the mask pattern.

[*36] 36. An apparatus according to claim 35, further comprising a projection optical system for projecting an image of the mask pattern onto the substrate.

[*37] 37. A device manufacturing method, for use with an optical integrator, comprising the steps of:

changing the position of incidence of each ray of an off-axis light beam upon the optical integrator, toward or away from the center of the optical integrator, to define a plurality of secondary light sources by the optical integrator; and

thereafter, transferring a device pattern onto a substrate with the plurality of secondary light sources defined by the optical integrator.

[*38] 38. A method according to claim 37, wherein said transferring step comprises imaging the device pattern, illuminated with the plurality of secondary light sources, upon the substrate.

Pat. No. 5465175 printed in FULL format.

5,465,175

<=2> GET 1st DRAWING SHEET OF 4

Nov. 7, 1995

Autostereoscopic display device

INVENTOR: Woodgate, Graham J., Oxfordshire, United Kingdom
Ezra, David, Oxfordshire, United Kingdom

ASSIGNEE-AT-ISSUE: Sharp Kabushiki Kaisha, Osaka, Japan (03)

APPL-NO: 150,369

FILED: Nov. 10, 1993

FOR-PRIOR:
Nov. 11, 1992 United Kingdom 9223652

INT-CL: [6] G02B 27#22; G02B 27#12; G02F 1#133.5

US-CL: 359#463; 349#15; 359#462; 359#464; 359#619; 359#621;

CL: 359;349;

SEARCH-FLD: 359#462, 463, 464, 619, 621, 626, 277, 48, 49, 41

REF-CITED:

U.S. PATENT DOCUMENTS

3,858,001	12/1974	* Bonne	178#6.5
4,957,351	9/1990	* Shioji	350#348
5,062,689	11/1991	* Koehler	359#230
5,132,839	7/1992	* Travis	359#462

FOREIGN PATENT DOCUMENTS

0262955	4/1988	* European Patent Organization
0354851	2/1990	* European Patent Organization
0389842	10/1990	* European Patent Organization
1273062	5/1972	* United Kingdom
2206763	1/1989	* United Kingdom
2252175	7/1992	* United Kingdom

OTHER PUBLICATIONS

Office Action issued Feb. 8, 1993 by British Patent Office for application GB 9223652.0.
Search Report for European Appl. 93308821.3 mailed Mar. 8, 1994.

PRIM-EXMR: Dzierzynski, Paul M.

ASST-EXMR: Chang, Audrey Y.

LEGAL-REP: Renner, Otto, Boisselle & Sklar

CORE TERMS: display, array, light source, screen, optical, lenses, diffuser, observer, plane, modulator, lenticular, spatial, pitch, barrier, lenticule, eye, illuminated, aperture, parallax, divergent, region, converging, sandwich, hybrid, beam, slice, progressively, modulating, interlaced, appearance

ABST:
An auto stereoscopic 3D display comprises a hybrid sandwich comprising a first lenticular screen, a spatial light modulator, a diffuser, and second lenticular screen. A plurality of light sources produce in turn divergent light beams which are modulated by the modulator with two interlaced views. The hybrid sandwich projects the views in different directions towards an observer. The different 2D views are thus visible from directions corresponding to the directions in which the views were captured during recording of a 3D image. Each eye of the observer sees a single view across the whole of the display.

NO-OF-CLAIMS: 21

EXMPL-CLAIM: <=7> 1

NO-OF-FIGURES: 8

NO-DRWNG-PP: 4

SUM:

The present invention relates to a display. Such a display may be used as a non-holographic three-dimensional (3D) display which is capable of forming a 3D image of opaque moving objects.

A known type of 3D display creates an illusion of a 3D image to a human observer by displaying a plurality of two-dimensional (2D) images in sequence. Each of the 2D images comprises a view of an object from a particular direction and is replayed in that direction. The perceived quality of 3D images provided by such techniques improves as the size of the display is increased.

GB-A-2 206 763 discloses a stereoscopic display apparatus in which light, from a light source positioned in the focal plane of a converging lens, is converted into parallel rays of light before being passed through a spatial light modulator.

U.S. Pat No. 5,062,689 discloses a projection display in which light is modulated by a spatial light modulator and then imaged on a screen.

U.S. Pat No. 3,858,001 discloses a stereoscopic display apparatus in which first and second images are polarised in first and second directions, respectively. The viewer wears spectacles containing analysers so that each eye receives only a respective image.

GB-A-1 273 062 discloses a stereoscopic display apparatus in which an image on a CRT is displayed through an array of lenses or pin holes. British Patent Application No. 9210399.3 discloses a 3D display in which temporal and spatial multiplexing are used to provide an autostereoscopic 3D image. By combining temporal and spatial multiplexing, an increased number of 2D views can be provided. However, the number of 2D views is limited by the maximum update rate and resolution of presently available spatial light modulators (SLM).

When a display of this type is increased in size so as to provide a relatively large display, each eye of an observer located at a given position will not see the same 2D view across the whole of the screen. Instead, the eye will see juxtaposed vertical slices of two or more different views on the screen with each slice having a width which is dependent on the position of the observer with respect to the display and on the display optical geometry. Each eye sees a different set of view slices which would give the appearance of a 3D image. However, the view slices can cause problems in the perception of a 3D image.

If a limited number of 2D views is available because of limited SLM update rate and resolution, then there may be an insufficient number of view slices to fill the display while maintaining the correct imaging directions for each view, so that the observer sees a 3D image over only part of the display. Thus, the display size is limited by the maximum update rates and resolutions of presently available SLMs.

According to the present invention, there is provided a display for producing an autostereoscopic image, comprising at least one light source for producing a divergent beam of light, and a spatial light modulator comprising a plurality of light modulating cells for modulating light passing therethrough from the at least one light source in accordance with image data, characterised by: a first array of lenses or apertures arranged to receive the divergent light beam from the or each light source, each of the lenses or apertures being arranged to produce an image of the or each light source at a common image plane such that each image is laterally displaced by a respective predetermined amount from an optical axis of the corresponding lens or aperture and the respective predetermined amounts vary progressively across the common image plane; and a second array of lenses or apertures having a common object plane which coincides with the common image plane.

The apertures may be elongate. Preferably the first array of lenses or apertures is located between the at least one light source and the spatial light modulator. Alternatively, the spatial light modulator may be located between the at least one light source and the first array of lenses or apertures.

The lenses of the first and second arrays are preferably converging lenses. For instance, the first and second arrays may comprise lenticular screens, for instance in the form of a plurality of parallel elongate lenticules having cylindrical convergent properties. The at least one light source may comprise a linear array of light sources extending perpendicularly to the lenticules. Such an arrangement may be used to provide horizontal parallax. Where both horizontal and vertical parallax is required, the first and second arrays may comprise 2D arrays of lenses, for instance in the form of microlens arrays. The lenses may be of the spherical convergent type and the at least one light source may comprise a two dimensional array of light sources. In either case, the light sources may be illuminated one at a time sequentially by suitable control

means. The or each light source may be contiguous with the or each adjacent light source.

The pitch of the lenses or apertures of the first array may be substantially equal to the pitch of the cells of the spatial light modulator. This pitch may be less than the pitch of the lenses or apertures of the second array, which may for instance be an integer multiple of the pitch of the lenses or apertures of the first array and the pitch of the cells of the modulator. A diffuser may be located between the modulator and the second array.

The diffuser is preferably located at or adjacent a common focal plane of the lenses of the second array, and at an image plane of the or each light source imaged by the lenses of the first array.

Alternatively, a field lens may be interposed between the first and second arrays.

An opaque barrier may be disposed between the modulator or diffuser and the second array for blocking transverse light paths.

It is thus possible to provide a display which is capable of being used as a large 3D display with each eye of an observer at a given position observing a single 2D view across the whole of the display. The eyes of the observer see different 2D views, thus giving the appearance of a 3D image. Such a display has many possible uses, for instance in television, computer aided design, medical imaging, video games, simultaneous 3D and 2D presentation, and virtual reality displays.

DRWDESC:

The invention will be further described, by way of example, with reference to the accompanying drawings, in which:

FIG. 1 is a diagrammatic plan view of a display of the type disclosed in British Patent Application No. 9210399.3;

FIG. 2 illustrates the appearance of a large display of the type shown in FIG. 1 when seen with one eye of an observer;

FIG. 3 is a diagrammatic plan view of a 3D display constituting a first embodiment of the invention;

FIG. 4 illustrates diagrammatically part of the display of FIG. 3 in more detail; and

FIGS. 5, 6, 7, and 8 are diagrammatic plan views of 3D displays constituting second, third, fourth, and fifth embodiments, respectively, of the invention.

Like reference numerals refer to like parts throughout the drawings.

DETDESC:

The display shown in FIG. 1 comprises a linear array of N light sources 1 to 8 where N-8 in the arrangement shown. The light sources 1 to 8 are contiguous

so as to form a continuous strip. The light sources are connected to a control circuit 9, which causes the light sources to be illuminated one at a time repetitively in order, FIG. 1 indicating that the light source 5 is illuminated. The linear array of light sources 1 to 8 is disposed in the focal plane of an illumination or collimating system 10, which is shown as a plano-convex lens having a cylindrical convex surface. The system 10 produces collimated light from each point of each of the light sources 1 to 8. Because the light sources have finite dimensions, the light output of the collimating system has a spread of angles.

Collimated light from the lens 10 is directed towards a hybrid sandwich 11 at an angle which is determined by which of the light sources 1 to 8 is presently illuminated. The hybrid sandwich comprises a lenticular screen (LS1) 12 formed by a plurality of contiguous cylindrical converging lens elements or lenticules having a horizontal pitch p. The screen 12 is followed by a SLM 13 in the form of a 2D liquid crystal device which is connected to the control circuit 9. The SLM 13 comprises a 2D array of picture elements whose light transmission properties (and colour transmission properties for a colour display) are controlled by the control circuit 9.

The SLM is followed by a diffuser 14 which is separated by a grid or barrier 15 for blocking lateral light paths from a further lenticular screen (LS2) 16. The screen 16 is similar to the screen 12 but has a horizontal pitch equal to Mp, where M is an integer greater than 1.

In use, the light rays from the illuminated light source 5 are collimated into parallel light rays by the system 10 and are focused by the screen 12 through the SLM 13 onto the diffuser 14. The picture elements of the SLM 13 are controlled by the control circuit so as to provide, for instance, two views of the image taken from different directions during image capture. The two views are interlaced such that alternate strip portions correspond to a respective one of the views.

The picture elements of the SLM 13 control the amount (and colour for a colour display) of light passing through the SLM so that a 2D array of images of the light source 5 is formed on the diffuser 14 corresponding to the two interlaced views. Each of the lenticules of the screen 16 converts the images on the diffuser 14 into output ray bundles whose angles of emission from the hybrid sandwich 11 depend on the lateral locations of the images on the diffuser 14 with respect to the optical axes of the lenticules. The two views represented on the SLM 13 are therefore visible from different angles corresponding to the angles of the object from which the views were taken during image capture. The grid or barrier 15 prevents each lenticule of the screen 16 from imaging the light images formed on the diffuser 14 and associated with adjacent lenticules of the screen 16.

After the light source 5 has been actuated for a predetermined time, the control circuit 9 deactivates the light source 5 and causes the SLM 13 to display the next pair of interlaced views. The next light source 4 is then activated and the screen 12 images the light through the SLM 13 onto regions of the diffuser 14 which are laterally displaced with respect to the images formed when the light source 5 is illuminated. Thus, the lenticular screen 16 provides output ray bundles directed at different angles corresponding to the directions of the view of the object during image capture.

This sequence of operation continues until each of the light sources of the linear array has been illuminated in turn, with the views represented on the SLM corresponding to a single "frame" of the 3D image. The whole sequence is then repeated for new sets of views representing consecutive frames constituting consecutive 3D images, the rate of repetition being sufficiently large to provide a substantially flicker-free image. The number of views making up each 3D image is equal to M x N. Although FIG. 1 shows a display capable of providing 16 views per image, practical SLMs may have refresh rates limited to 100 Hz so that, in order to provide a flicker-free image, the array of light sources may comprise only two sources. Similarly, practical SLMs may have resolution limits such that only two views at a time can be produced. Thus, the number of views per frame may be limited to four.

It is intended that, for each given position of the observer within a region in front of the display for which a 3D effect is to be produced, each eye of the observer sees only one of the views across the whole display in the direction corresponding to that from which the 2D view was captured. However, for relatively large 3D displays, the limited resolution and frame rate of the SLM 13 and the optical geometry of the display can result in the appearance illustrated in FIG. 2. Thus, in a middle region 18 of the display, one eye of the observer sees part of a first view. However, at edge regions 19 and 20 of the display, the same eye of the observer sees parts of second and third different views. The view slices can cause problems in the perception of a 3D image.

The display shown in FIG. 3 differs from that shown in FIG. 1 in that the collimating system 10 is omitted. Also, the array of light sources is shown as comprising only four such sources 1 to 4. Otherwise, the control circuit 9 and the hybrid sandwich 11 are substantially identical to the corresponding parts of the display of FIG. 1.

In use, the control circuit 9 controls the light sources 1 to 4 and the SLM 13 as described with reference to FIG. 1. However, the hybrid sandwich 11 receives a divergent beam of light from each of the light sources 1 to 4, so that the light sources are imaged by the lenticules of the screen 12 through the SLM 13 onto different positions on the diffuser 14 located at an image plane of the first array. When each light source is illuminated, its image on the diffuser 14 is at the same position as in the display of FIG. 1 for the lenticule of the screen 12 on whose optical axis the light source is located, i.e. it has a lateral displacement of zero. For other lenticules, the light source image is laterally displaced progressively further towards the edge of the diffuser as the lateral distance of the lenticule from the abovementioned optical axis increases. This offset is illustrated at 21 In FIG. 4 with the light source 3 illuminated. The lateral displacement therefore varies progressively across the whole of the diffuser, changing sign when the normal from the illuminated light source to the diffuser is passed. Thus, the direction of light emerging from each lenticule of the screen 16 varies progressively across the display, so that each view of the interlaced pair of views is projected towards a single point instead of in a single direction as for the display of FIG. 1. Thus, an observer 17 will see a single but different 2D view with each eye over the whole of the display so that the appearance of a full screen 3D image will be produced. FIG. 4 illustrates at 24 the points or regions towards which the two views produced when the light source 3 is illuminated are projected.

The diffuser 14 may be replaced by a field lens.

Such an arrangement provides a limited region from which an observer may perceive the 3D effect. For instance, for a display of size 0.5 m with an observer located 1 m from the front surface, a display providing four views permits the observer to maintain a 3D image within a region which extends approximately 200 mm laterally on either side of a normal to the centre of the display and 260 mm in front of and behind the observer position. An SLM frame rate of 100 Hz permits a nonflickering image to be perceived.

When the first array is a parallax barrier, it no longer has a single image plane, but instead any plane parallel to the first array can be an image plane. Similarly, when the second army is a parallax barrier, any one of a plurality of planes parallel to the second array and between the first and second arrays may serve as an object plane.

FIG. 5 illustrates a display which differs from that of FIG. 3 in that the lenticular screens 12 and 16 are replaced by parallax barriers 22 and 23, respectively.

Each of the barriers comprises a plurality of slits arranged perpendicularly to the axis of the array of light sources 1 to 4. The pitch of the slits of the barrier 22 is equal to the pitch of the elements of the SLM 13 , whereas the pitch of the slits of the barrier 23 is equal to twice that of the barrier 22. Operation of this display is the same as that of the display shown in FIG. 3.

FIG. 6 shows a display which differs from that of FIG. 3 in that the lenticular screen 12 is replaced by a parallax barrier 22 of the type shown in FIG. 5. The display of FIG. 7 differs from that shown in FIG. 3 in that the lenticular screen 16 is replaced by a parallax barrier 23 of the type shown in FIG. 5. The operations of the displays of FIGS. 6 and 7 are the same as that of the display shown in FIG. 3.

FIG. 8 shows a display; which differs from that of FIG. 3 in that the lenticular screen 12 follows the SLM 13 and in that the grid or barrier 15 has been omitted (although it may be included). The SLM 13 thus modulates the divergent light beams from the light sources 1, 2 (only two are shown in FIG. 8) and the modulated beams are imaged onto the diffuser 14 by the lenticular screen 12.

The lenticular screen 12 and/or the lenticular screen 16 may be replaced by a respective parallax barrier of the type shown in FIGS. 5 to 7. Although the lenticular screen 12 (or the parallax barrier) may be located behind the SLM 13 as shown in FIG. 8, it is at present preferred to place it in front of the SLM 13 as shown in FIGS. 3 to 7.

It is thus possible to provide a relatively large 3D display in which, from any point within a region from which the 3D effect may be viewed, each eye of an observer sees a single view extending across the whole of the display. This is achieved without the need to increase the frame rate or resolution of the SLM.

CLAIMS: What is claimed:

[*1] 1. A display for producing an autostereoscopic image, comprising:

at least one light source for producing a divergent beam of light;

a spatial light modulator comprising a plurality of light modulating cells for modulating light passing therethrough from the at least one light source in accordance with image data;

a first array of optical components arranged to receive the divergent light beam from the at least one light source, each of the optical components being arranged to produce an image of the at least one source at a common image plane such that each image is laterally displaced by a respective predetermined amount from an optical axis of the corresponding optical component and the respective predetermined amounts vary progressively across the common image plane; and

a second array of optical components having a common object plane which coincides with the common image plane.

[*2] 2. A display as claimed in claim 1, wherein the first array of optical components is located between the at least one light source and the spatial light modulator.

[*3] 3. A display as claimed in claim 1, wherein the spatial light modulator is located between the at least one light source and the first array of optical components.

[*4] 4. A display as claimed in claim 1, wherein the optical components of the first array are converging lenses.

[*5] 5. A display as claimed in claim 1, wherein the optical components of the second array are converging lenses.

[*6] 6. A display as claimed in claim 4, wherein the optical components of the second array are converging lenses, and the first and second arrays comprise first and second lenticular screens, respectively.

[*7] 7. A display as claimed in claim 6, wherein each of the first and second lenticular screens comprises a plurality of parallel elongate lenticules having cylindrical convergent properties.

[*8] 8. A display as claimed in claim 7, wherein the at least on light source comprises a linear array of light sources extending perpendicularly to the lenticules.

[*9] 9. A display as claimed in claim 4, wherein the optical components of the second array are converging lenses, end the first end second arrays comprise first and second two dimensional arrays of lenses, respectively.

[*10] 10. A display as claimed in claim 9, wherein the optical components of the first and second arrays have spherical convergent properties.

[*11] 11. A display as claimed in claim 9, wherein the at least one light source comprises a two dimensional array of light sources.

[*12] 12. A display as claimed in claim 1, wherein the pitch of the optical components of the first array is substantially equal to the pinch of the light modulating cells of the spatial light modulator.

[*13] 13. A display as claimed in claim 12, wherein the pitch of the optical components of the second array is greater than the pitch of the optical components of the first array.

[*14] 14. A display as claimed in claim 13, wherein the pitch of the optical components of the second array is substantially equal to the product of the pitch of the optical components of the first array and an integer greater than 1.

[*15] 15. A display as claimed in claim 1, wherein a diffuser is disposed at the common image plane.

[*16] 16. A display as claimed in claim 1, wherein a field lens is disposed at the common image plane.

[*17] 17. A display as claimed in claim 1, wherein the spatial light modulator comprises a liquid crystal device.

[*18] 18. A display as claimed in claim 1, wherein the at least one light source comprises a plurality of light sources and in that each of the light sources is contiguous with the or each adjacent light source.

[*19] 19. A display as claimed in claim 18, further comprising control means for sequentially illuminating the light sources.

[*20] 20. A display as claimed in claim 19, wherein the control means is arranged to control the spatial light modulator in accordance with a plurality of sequentially presented images representing a frame of a three dimensional image, each image comprising at least one view.

[*21] 21. A display as claimed in claim 1, wherein the optical components of the first array produce the image of the at least one light source by refracting the received divergent light beam.

Pat. No. 5936759 printed in FULL format.

5,936,759

<=2> GET 1st DRAWING SHEET OF 2

Aug. 10, 1999

Arrangement for shifting optical images between individual channels

INVENTOR: Buttner, Knut, Uberlingen, Federal Republic of Germany

ASSIGNEE-AT-ISSUE: Bodenseewerk Geratetechnik GmbH, Uberlingen, Federal Republic of Germany (03)

APPL-NO: 27,910

FILED: Feb. 23, 1998

FOR-PRIOR:
Feb. 25, 1997 German Democratic Republic 19707432

INT-CL: [6] G02B 26#00

US-CL: 359#291; 359#618; 359#619; 359#627; 250#208.1

CL: 359;250

SEARCH-FLD: 359#290, 291, 298, 299, 300, 315, 247, 618, 619, 627, 630; 250#208.1, 208.2

REF-CITED:

U.S. PATENT DOCUMENTS

5,049,740	9/1991	*	Pines et al.	250#235
5,119,454	6/1992	*	McMahon	359#290
5,444,572	8/1995	*	Gal et al.	359#619
5,448,395	9/1995	*	Lopez et al.	359#224
5,519,206	5/1996	*	Uwira	250#208.1
5,557,431	9/1996	*	Pepper	359#300
5,596,185	1/1997	*	Bross et al.	250#208.1
5,640,479	6/1997	*	Hegg et al.	359#291
5,691,836	11/1997	*	Clark	359#247
5,726,795	3/1998	*	Betin et al.	359#300

FOREIGN PATENT DOCUMENTS

0663770 A1	7/1995	*	European Patent Office (EPO)
43 38 390 A 1	11/1993	*	Federal Republic of Germany
44 02 775 C1	7/1995	*	Federal Republic of Germany
2 146 137	4/1985	*	United Kingdom

OTHER PUBLICATIONS

William L. Wolfe Apr. 27, 1998, "Introduction To Infrared System Design".
Leo Beiser, Apr. 27, 1998 Nov. 1, 1995/vol. 34, No. 31/Applied Optics pp.

7307-7317, "Fundamental Architechture of Optical Scanning Systems".

PRIM-EXMR: Ben, Loha

LEGAL-REP: McDermott, Will & Emery

CORE TERMS: optical, channel, plane, mirror, imaging, intermediate, micro-mechanical, shiftable, sub-system, shifting, sensor, fast, conjugately, image-resolving, sequence, grating, path, rays, actuated, beam, actuating, lens, detected, imaged, heat, arrangment, optionally, optically, blurring, tilted

ABST:

The invention relates to an arrangement for shifting optical images between individual channels. A plurality of imaging optical systems adapted to image conjugately upon each other, in an associated shiftable optical channel, an associated plane and an intermediate image plane, comprise a micro-mechanical mirror system (mirror array) arranged in the intermediate image plane and having a grid of mirror elements adapted to be tilted and actuated. A further imaging optical system is adapted to image conjugately upon each other, in a common channel, the intermediate image plane and a plane associated with the common channel. The mirror elements of the micro-mechanical system are adapted to be actuated in such a manner, that they optically connect optionally one of the shiftable channels to the common channel.

NO-OF-CLAIMS: 9

EXMPL-CLAIM: <=13> 1

NO-OF-FIGURES: 6

NO-DRWNG-PP: 2

SUM:

BACKGROUND OF THE INVENTION

This invention relates to an arrangement for shifting optical images between individual channels.

Such an arrangement can, for example, serve to observe individual sections of a field of view or other individual objects by each an optical system in individual optical channels and to guide in fast sequence the detected images to a common optical channel and, for example, to an image-resolving sensor located in the common optical channel. This is the function of an "optical multiplexer". However, such an arrangement can also serve to guide an image generated in the common optical channel to individual parallel channels. This is the function of an "optical demultiplexer".

Prior art arrangements of this type operate with rotating polygon mirrors. One disadvantage of such arrangements is that shifting only can be effected in one single sequence exactly predetermined. A further disadvantage is image blurring due to the movement of the polygon mirror. This image blurring limits the rotary speed of the polygon mirror and, thus, the possible shift frequency (multiplex rate).

Other prior art arrangements operate by displacing elements of the imaging optical system. Such displacement of elements of the imaging optical system also limits the multiplex rate due to the moments of inertia and the inertial forces of the elements to be displaced.

Furthermore, it is known to image individual objects through individual optical channels or paths and a common lens system upon a single detector, the individual optical channels or paths being shifted individually. This requires a large numerical aperture of the common lens system. In addition, problems arise due to scattered light. EP-A-0 469 293 describes a micro-mechanical mirror system having a plurality of electrically actuated mirror elements. A similar micro-mechanical mirror system is described in EP-A-0 657 760.

SUMMARY OF THE INVENTION

It is the object of the invention to provided an arrangement for shifting optical images between individual optical channels.

Another object of the invention is to provide an arrangment for shifting optical images between individual optical channels with high speed.

Still another object of the invention is to provide an arrangment for shifting optical images between individual optical channels without image blurring.

Still another object of the invention is to provide an arrangment for shifting optical images between individual optical channels, by means of which the shifting between the optical channels can be effected in arbitrary sequence.

Still another object of the invention is to provide an arrangment for shifting optical images between individual optical channels, by means of which the problems of prior art arrangements arising due to large masses or the necessity of a large numerical aperture are avoided.

These and other objects are achieved by an arrangement for shifting optical images between individual channels, comprising: a plurality of imaging optical systems adapted to image conjugately upon each other, in an associated shiftable optical channel, an associated plane and an intermediate image plane; a micro-mechanical mirror system (mirror array) arranged in said intermediate image plane and having a grid of mirror elements adapted to be tilted and actuated; a further imaging optical system having an optical axis and adapted to image conjugately upon each other, in a common channel, said intermediate image plane and a plane associated with said common channel; and actuating means for actuating said mirror elements of said micro-mechanical system in such a manner, that said mirror elements optically connect optionally one of said shiftable channels to said common channel.

Each of the imaging optical systems in the shiftable channels generates, for example, a real image of the associated plane in the intermediate image plane. The micro-mechanical mirror system reflects the image from one of the shiftable channels into the common channel and the further optical system images the image in the plane associated with the common channel. The intermediate image on the micro-mechanical mirror system acts as a luminous image for the further optical system. Due to the fact, that a real image is generated on the

micro-mechanical mirror system, there are no interfereces. Shifting from one of the shiftable channels to another by means of correspondingly actuating the mirror elements can be effected very fast and in arbitrary sequence of the channels. Inertial forces are neglectable. There are no image blurring. Using the same optical arrangement, by inversing the direction of the rays, also the plane associated with the common channel can be imaged consecutively on the planes associated with the individual shiftable channels.

Further objects and features of the invention will be apparent to a person skilled in the art from the following specification of a preferred embodiment when read in conjunction with the appended claims.

DRWDESC:
BRIEF DESCRIPTION OF THE DRAWING

The invention and its mode of operation will be more clearly understood from the following detailed description when read with the appended drawing in which:

FIG. 1 shows a single imaging path of rays in a first embodiment of an arrangement for shifting optical images between individual channels;

FIG. 2 shows an arrangement for shifting optical images between two individual channels operating with imaging paths of rays according to FIG. 1;

FIG. 3 shows is a schematic partial view at enlarged scale of a micro-mechanical mirror system, which is used in the embodiment of FIGS. 1 and 2, the micro-mechanical mirror system being in a shift position corresponding to FIG. 1;

FIG. 4 shows the micro-mechanical mirror system of FIG. 3 in another shift position;

FIG. 5 shows, at enlarged scale, a mirror grating, which is used in the paths of rays of FIGS. 1 and 2; and

FIG. 6 shows a single imaging path of rays in a second embodiment of an arrangement for shifting optical images between two individual channels.

DETDESC:

DESCRIPTION OF THE PREFERRED EMBODIMENTS

Referring now to FIG. 1, there is shown an object, which is located in a plane 14 associated with the "shiftable" optical channel 12. The plane 14 can, for example, be located at infinity. The plane extends perpendicularly to the optical axis 16 of a first imaging optical sub-system 18. The optical sub-system 18 is illustrated by a lens in FIG. 1.

The first optical sub-system 18 images the plane 14 in a mirror plane 20 (or inversely). A mirror grating of parallel mirror strips inclined with respect to the mirror plane 20 is located in the mirror plane 20. Such a mirror grating is schematically illustrated in FIG. 5 at enlarged scale.

A second imaging optical sub-system 26 images the mirror plane 20 in an intermediate image plane 28 (or inversely). The second imaging optical

sub-system is likewise illustrated by a lens in FIG. 1. The mirror plane 20 and the intermediate image plane 28 are inclined relative to each other. The mirror plane 20 and the intermediate image plane 28 are not perpendicular to the optical axis of the second imaging optical sub-system. The mirror plane 20, the second imaging optical sub-system 26 and the intermediate image plane 28 are arranged relative to each other in a manner, such that Scheimpflug's condition is fulfilled: The mirror plane 20 and the intermediate image plane 28 intersect with the principal plane of the second imaging optical sub-system 26 in a straight line. When Scheimpflug's condition is fulfilled, the mirror grating 22 reflects the imaging light beam from the first imaging optical sub-system to the second imaging optical sub-system. In this way, the sharp real image of the object generated on the mirror grating 22 is sharply imaged in the intermediate image plane 28.

The sharp real image of the object 10 generated in the mirror plane acts as a luminous object for the second imaging optical sub-system 26. All of the mirror strips 24 of the mirror grating 22 are substantially located in the plane of sharpness of this image. However, the imaging light beam is reflected in a direction towards the second imaging optical sub-system. No interferences appear, because a real image is generated in the plane of the mirror grating 22.

A micro-mechanical mirror system 30 is located in the intermediate image plane. This micro-mechanical mirror system can be designed according to the above mentioned EP-A-0 469 293 or EP-A-0 657 760. The mirror system 30 consists of a two-dimensional grid of mirror elements 34 (FIGS. 3 and 4). The mirror elements 34 can be actuated by an actuating circuit 32. This is known per se and therefore not illustrated in detail herein. In the present embodiment, all of the mirror elements 34 are actuated in the same way. In the position of the mirror elements 34 in FIGS. 1 and 3, the mirror elements 34 are orientated to reflect the imaging light beam in a "common" optical channel 36 in a direction towards a further imaging optical system 38 along its optical axis 40. The further imaging optical system 38 sharply images the micro-mechanical mirror system 30 in a plane 42. The plane 42 is the plane associated with the common optical channel 36.

The sharp image generated in the intermediate image plane 28 on the micro-mechanical mirror system 30 acts as a luminous object for the further imaging optical system 38. The mirror elements 34 are practically located in the plane of sharpness of the image. The mirror elements 34 arc orientated such that they guide the energy of the imaging light beam to the further imaging optical system 38.

The direction of the rays can, of course, also be inverted: An object located in the plane 42 can be imaged through intermediate images in the intermediate image plane 28 and the mirror plane 20 in the plane 14.

FIG. 1 shows the path of rays for one channel 12 and the common channel 36. In addition to the channel 12, further channels are adapted to be optionally optically connected in a corresponding manner to the common channel 36 by the micro-mechanical mirror system 30. FIG. 2 shows the arrangement with two shiftable channels 12 and 12A. The optical design of the channel 12A corresponds mirror-invertly to the channel 12. Corresponding elements in the channel 12A are designated by the same reference numerals as in the channel 12, but additionally marked by "A".

The micro-mechanical mirror system 30 is adjustable in order to shift the channels between two positions, which are illustrated in FIGS. 3 and 4. In the position illustrated in FIG. 3, the imaging light beam is guided from the channel 12 into the common channel 36. The image of an object detected by the imaging optical sub-system 18 in the associated plane 14 is generated in the plane 42. In the position illustrated in FIG. 4, the imaging light beam is guided from the channel 12A into the common channel 36. The image of an object detected by the imaging optical sub-system 18A in the associated plane is generated in the plane 42.

In the same manner, more than two shiftable channels can be arranged about the optical axis 40 of the imaging optical system 38, for example two further channels in the plane perpendicular to the paper plane of FIG. 2. A section taken along a plane containing the optical axis 40 and being perpendicular to the paper plane would then look the same way as FIG. 2. In this case, the mirror elements 34 of the micro-mechanical mirror system have to be arranged to be tilted about two axes.

Due to the symmetric arrangement of the micro-mechanical mirror system 30 with respect to the optical axis 40 of the imaging optical system 38 and the symmetric arrangement of the channels 12 and 12A, there are no vignetting of the imaging light beam.

FIG. 6 shows a "shiftable" channel and the common channel in a modified embodiment.

In the embodiment of FIG. 6, an object 46 in a plane 48 is imaged by an imaging optical system 50 in the intermediate image plane 28. Here, the imaging optical system 50 is a decentered lens system. This makes it possible to do without a further intermediate image as in the "mirror plane" of FIGS. 1 and 2. The plane 48 is directly imaged upon the intermediate image plane 28. The micro-mechanical mirror system and the common channel correspond to those in FIGS. 1 and 2. Therefore, corresponding elements are designated by the same reference numerals in FIG. 6 as in FIGS. 1 and 2. The imaging optical system 50 constitutes one channel 52 of the "shiftable" optical channels. Several such shiftable channels are arranged about the optical axis 40 of the imaging optical system 38.

The described optical multiplexers or demultiplexers can be used in several different applications.

An image-resolving sensor, for example a matrix sensor, can be arranged in the plane 42. Then, the individual shiftable channels 12, 12A . . . can observe different sectors of an extended field of view. Through the micro-mechanical mirror system 30, the different sectors can be consecutively detected in fast and, if required, variable sequence by the image-resolving sensor. In order to test infrared sensors in seeker heads of target-tracking missiles, it is required to generate quickly varying heat images in order to, for example, simulate a quickly movable hot target. It is difficult to generate heat images, which change quickly. The temperature of the surface element representing the heat image can not be changed quickly. Then, it is possible to generate different heat images changing just inertially in the planes associated with the individual channels 12, 12A . . . and to progress the channels by means of the micro-mechanical mirror system in order to simulate fast variations. In both cases, the "source" of the image information is located in the planes 14 of

the shiftable channels, whereas a "sink" of the image information is located in the plane 42 associated with the common channel. The arrangement operates as "optical multiplexer".

However, it is also possible, by means of the micro-mechanical mirror system, to guide an object located in the plane 42 in fast sequence consecutively to the individual optical channels. This can, for example, be used to detect fast actions using image-resolving sensors, which are relatively sluggish. Such an image-resolving sensor can be arranged in each one of the planes associated with a shiftable optical channel, for example in the plane 14. A fast action can be detected by fast shifting in that each of the relatively sluggish image-resolving sensors just detects one phase of this action.

CLAIMS: I claim:

[*1] 1. An arrangement for shifting optical images between individual channels, comprising:

a plurality of imaging optical systems adapted to image conjugately upon each other, in an associated shiftable optical channel, an associated plane and an intermediate image plane;

a micro-mechanical mirror system (mirror array) arranged in said intermediate image plane and having a grid of mirror elements adapted to be tilted and actuated;

a further imaging optical system having an optical axis and adapted to image conjugately upon each other, in a common channel, said intermediate image plane and a plane associated with said common channel; and

actuating means for actuating said mirror elements of said micro-mechanical mirror system in such a manner, that said mirror elements optically connect optionally one of said shiftable channels to said common channel.

[*2] 2. The arrangement of claim 1, wherein said imaging optical systems of said shiftable optical channels comprise:

a first imaging optical sub-system adapted to image conjugately upon each other said plane associated with said corresponding channel and a mirror plane;

a mirror arrangement arranged in said mirror plane; and

a second imaging optical sub-system adapted to image conjugately upon each other said mirror plane and said intermediate image plane.

[*3] 3. The arrangement of claim 2, wherein:

said mirror plane, said second imaging optical sub-system and said intermediate image plane are arranged relative to each other in a position, in which Scheimpflug's condition is fulfilled; and

said mirror arrangement forms a mirror grating of narrow mirror strips inclined with respect to said mirror plane and adapted to deflect an imaging path of rays from said first imaging optical sub-system to said second imaging optical sub-system and to said micro-mechanical mirror system located in said

intermediate image plane.

[*4] 4. The arrangement of claim 1, wherein said imaging optical systems of said shiftable optical channels each have a decentered lens system adapted to image directly conjugately upon each other said plane associated with said optical channel and said intermediate image plane.

[*5] 5. The arrangement of claim 1, wherein said plurality of imaging optical systems each forming an optical channel is arranged about an axis extending perpendicularly to said intermediate image plane and forming said optical axis of said further imaging optical system, each of said imaging optical systems imaging an associated plane in said intermediate image plane.

[*6] 6. The arrangement of claim 5, wherein each of said shiftable optical channels detects a sector of an extended field of view, said micro-mechanical mirror system shifting in fast sequence said individual shiftable channels to said common channel.

[*7] 7. The arrangement of claim 1, wherein an image-resolving sensor is arranged in said plane associated with said common optical channel.

[*8] 8. The arrangement of claim 7, wherein means generating test images are arranged in said planes associated with said shiftable channels, said micro-mechanical mirror system being adapted to shift in fast sequence said individual shiftable channels to said common channel.

[*9] 9. The arrangement of claim 8, wherein:

an infrared image-resolving sensor is arranged in said plane associated with said common optical channel; and

said means generating test images are adapted to generate heat images.

Pat. No. 6014244 printed in FULL format.

6,014,244

<=2> GET 1st DRAWING SHEET OF 13

Jan. 11, 2000

Multi-port optical circulator utilizing imaging lens and correction optical element

INVENTOR: Chang, Kok-Wai, Sunnyvale, California

ASSIGNEE-AT-ISSUE: Hewlett-Packard Company, Palo Alto, California (02)

ASSIGNEE-AFTER-ISSUE: Date Transaction Recorded: Apr. 28, 2000
MERGER (SEE DOCUMENT FOR DETAILS).
HEWLETT-PACKARD COMPANY, A DELAWARE CORPORATION P.O. BOX 272400 INTELLECTUAL PROPERTY ADMINISTRATION FORT COLLINS, COLORADO 80528-959
Reel & Frame Number: 010841/0649

Date Transaction Recorded: May 30, 2000
ASSIGNMENT OF ASSIGNOR'S INTEREST (SEE DOCUMENT FOR DETAILS).
AGILENT TECHNOLOGIES INC INTELLECTUAL PROPERTY ADMINISTRATION P.O. BOX 58043, M/S 51UPD SANTA CLARA, CALIFORNIA 95052-804
Reel & Frame Number: 010977/0540

APPL-NO: 100,666

FILED: Jun. 18, 1998

INT-CL: [6] G02F 1#09

US-CL: 359#281; 385#11

CL: 359;385

SEARCH-FLD: 385#33; 359#484, 487, 497, 499, 281; 372#703

REF-CITED:

U.S. PATENT DOCUMENTS

4,712,880	12/1987	*	Shirasaki	350#377
4,981,335	1/1991	*	Gaebe	350#96
5,204,771	4/1993	*	Koga	359#281
5,319,483	6/1994	*	Krasinski et al.	359#113
5,471,340	11/1995	*	Cheng et al.	359#281
5,566,259	10/1996	*	Pan et al.	385#11

FOREIGN PATENT DOCUMENTS

WO 97/22034	6/1997	*	World Intellectual Property Organization (WIPO)	G02#B2.728

PRIM-EXMR: Epps, Georgia

ASST-EXMR: Thompson, Timothy J

CORE TERMS: fiber, lens, beam, compensating, optical, focusing, polarization,

rotator, circulator, half-wave, propagating, multi-port, crystal, path, rearward, forward, propagation, lenses, rotation, port, rotated, input, nonreciprocal, travel, mirror, displaced, transmitted, array, 118-124, propagate

ABST:
A nonreciprocal optical device, preferably an optical circulator, and a method of transferring optical signals utilize a compensating lens coupled optically to a focusing lens. The compensating lens operates to correct misalignments caused by the focusing lens. The focusing lens and the compensating lens provide efficient coupling of optical fibers. Preferably, the compensating lens has a forward face with a number of flat surfaces that can refract light in a desired manner. In a first embodiment, two compensating lenses in optical series between two focusing lenses are utilized. In a second embodiment, only one compensating lens is utilized, but a mirror assembly is introduced so that polarization components of a light beam propagate through the compensating lens twice. In the first embodiment, the circulatory functions are accomplished by two optical assemblies and a shift plate. On the other hand, the circulatory functions in the second embodiment are performed by only one optical assembly and a shift plate. The single optical assembly is utilized twice in single transmission of a light signal, providing a compact optical device.

NO-OF-CLAIMS: 18

EXMPL-CLAIM: <=9> 1

NO-OF-FIGURES: 46

NO-DRWNG-PP: 13

SUM:

TECHNICAL FIELD

The invention relates generally to nonreciprocal optical devices and more particularly to an optical circulator that can accommodate transmissions among multiple optical fibers.

DESCRIPTION OF THE RELATED ART

Continuing innovations in the field of fiber optic technology have contributed to the increasing number of applications of fiber optics in different technologies. The flexibility and reliability of communication networks based upon transmission of light signals via optical fibers are greatly increased by the availability of assemblies such as optical circulators and isolators. Optical circulators enable a bidirectional fiber to be coupled to both an input optical fiber and an output optical fiber. Optical isolators provide forward propagation of light signals from an input optical fiber to an output optical fiber, while inhibiting light from propagating in the rearward direction from the output optical fiber to the input optical fiber.

U.S. Pat. No. 5,204,771 to Koga describes an optical circulator having three birefringent crystals and two nonreciprocal rotator assemblies. Each of the two nonreciprocal rotator assemblies is positioned between two adjacent

birefringent crystals. The nonreciprocal rotator assemblies are comprised of a Faraday rotator, a left half-wave plate, and a right half-wave plate. The left half-wave plate provides a rotation of polarization components of light beams in a direction that is opposite to the direction of rotation caused by the right half-wave plate. The optical circulator of Koga includes an input/output port on one face of the optical circulator assembly. On the opposite face, an output port and an input port are positioned such that the input port is located above the output port. The optical circulator of Koga operates to transmit light signals received by the input port to the input/output port. However, light signals that are received by the input/output port are directed to the output port, instead of being directed back to the input port.

Another optical circulator of interest is described in U.S. Pat. No. 5,471,340 to Cheng et al. In an attempt to reduce the number of required components for achieving optical isolation or circulation, the optical circulator of Cheng et al. utilizes a mirror at one end of an optical assembly. Adjacent input/output ports are situated at the end of the assembly opposite to the mirror. The optical assembly includes a first birefringent crystal, upper and lower half-wave plates, a first Faraday rotator, a second birefringent crystal, and a second Faraday rotator. In operation, a light beam enters the optical assembly from one of the input/output ports. The first birefringent crystal divides the light beam into two polarization components. The adjacent nonreciprocal Faraday rotator and the upper and lower half-wave plates properly align the polarization components for lateral displacement (walk-off) of one or both of the polarization components by the center birefringent crystal. The polarization components are rotated by the second Faraday rotator twice as the light beams are reflected by the mirror. The first birefringent crystal plate then recombines the two polarization components for output to a different input/output port.

There are a number of factors that must be considered in the design of optical circulators and isolators. U.S. Pat. No. 5,319,483 to Krasinski et al. identifies insertion loss and crosstalk as two performance-related design considerations. Insertion loss is the difference in power between input light and the light that exits the optical assembly. The primary causes of insertion loss are identified as absorption of light and imperfections of polarization separation and recombination. Crosstalk in an optical circulator is the transmission of light from an input fiber to a fiber which is not the intended output fiber. Krasinski et al. assert that the primary cause of crosstalk in optical circulators is back-reflection from the various optical elements in the assembly. The system described in the patent utilizes birefringent crystals instead of polarization splitting cubes in an attempt to provide more complete polarization separation, thereby reducing insertion loss and crosstalk. Moreover, the system is one in which the optical elements of the assembly are in optical contact with each other, thereby reducing back-reflections.

Another cause for insertion loss is dispersion of light beams when propagating through optical elements, which hinders efficient fiber-to-fiber coupling. One means to alleviate this concern is to use lenses to focus the light beams. Patent Cooperation Treaty application No. PCT/AU96/00800by Frisken, published on Jun. 19, 1997, International Publication No. WO 97/22034, describes an optical circulator having a pair of lenses between two optical assemblies. The pair of lenses operates to focus light beams propagating through the optical circulator. Each of the two optical assemblies includes a Faraday rotator and a half-wave plate positioned between two birefringent crystals. The two optical

assemblies perform separation, rotation, and recombination operations on polarization components of propagating light beams to facilitate circulation of light beams to and from optical fibers.

In addition to the above-identified performance-related concerns, there are manufacturing-related concerns. Preferably, the assembly is physically small, providing advantages with respect to the cost of materials and the ability to house a number of such assemblies. If there is an array of input/output ports at one side of an optical circulator or isolator, the core-to-core spacing between the ports (i.e., "pitch") may determine the width and the length of the assembly of optical elements. Conventionally, there is a pitch of at least 2 mm in order to accommodate the use of collimators. The minimum width of the assembly is the product of the pitch and the number of ports in the array. Rutile is a common material for forming the birefringent crystals that provide the desired walk-off displacements within the assembly. For each 1 mm of walk-off, the rutile crystal must have a thickness of approximately 10 mm. The thicknesses of the other optical elements in the assembly, e.g. the Faraday rotator, add to the total thickness dimension of the assembly.

While known optical circulators operate well for their intended purposes, improvements in performance and reduction in fabrication cost are desired in a design of optical circulators. What is needed is an optical circulator for coupling multiple optical fibers for transmitting signals, such as light signals within a communication network, with a high density of input/output ports and with a significant cost efficiency in the fabrication process.

SUMMARY OF THE INVENTION

A nonreciprocal optical device, preferably an optical circulator, and a method of transferring optical signals utilize a compensating lens coupled optically to a focusing lens. The compensating lens operates to correct misalignment caused by the focusing lens. Preferably, the compensating lens has a forward face with number of flat surfaces that can refract diverging light received from the rearward face of the compensating lens into parallel light. In addition, the compensating lens is able to receive parallel light on the forward face and refract the parallel light such that the light is emitted from the rearward face in a converging manner.

In a first embodiment of the invention, the nonreciprocal optical device includes two compensating lenses in optical series between two focusing lenses. The two focusing lenses are preferably identically shaped converging lenses. Although not critical to the invention, the focusing lenses may be configured to provide 1:4 imaging. Similar to the focusing lenses, the two compensating lenses are physically identical. The two compensating lenses are positioned such that the forward faces of the compensating lenses are face-to-face. Preferably, the four lenses are positioned such that the distance between the first focusing lens and the first compensating lens is equal to the distance between the second compensating lens and the second focusing lens. The focusing lenses and the compensating lenses provide efficient coupling of optical fibers. The circulatory functions are accomplished by two optical assemblies and a shift plate.

The first optical assembly includes a walk-off crystal, upper and lower half-wave plates, and a Faraday rotator. The first optical assembly operates

to separate a light beam into two orthogonal polarization components and rotates one of the two polarization components such that both polarization components are aligned to be shifted laterally, i.e., positive or negative x-direction, by the shift plate. The second optical assembly operates to recombine the two polarization components for output via a predetermined optical fiber. Preferably, the first and second optical assemblies are structurally identical. The only difference between the two optical assemblies is the orientation of the second optical assembly with respect to the first optical assembly. The second optical assembly is rotated 180o, such that forward and rearward faces of the second optical assembly are switched with respect to the faces of the first optical assembly.

The optical elements in the first optical assembly, and consequently the second optical assembly, can be configured in a number of alternative arrangements without affecting the operations of the first optical assembly and the second assembly. First, the walk-off crystal may have a walk-off direction in either vertical direction, i.e., positive or negative y-direction, to separate the polarization components of a light beam. Second, the upper and lower half-wave plates can be positioned either in front of the Faraday rotator or rearwardly of the Faraday rotator. The only criterion is that the half-wave plates are arranged such that one polarization component of a light beam travels through the upper half-wave plate, while the other polarization component travels through the lower wave plate. Preferably, each of the Faraday rotator and the half-wave plates provides a 45o rotation of polarization components. If the walk-off crystal has a walk-off direction in the positive y-direction, the Faraday rotator and the upper half-wave plate can provide clockwise rotations of a forward propagating polarization component, while the lower half-wave plate provides a counter-clockwise rotation. Alternatively, the Faraday rotator and the upper half-wave plate can provide counter-clockwise rotations, while the lower half-wave plate provides a clockwise rotation. If the walk-off crystal has a walk-off direction in the negative y-direction, the rotations of the upper and lower half-wave plates are reversed.

In the preferred embodiment, the shift plate is positioned between the two compensating lenses. The shift plate only displaces forward propagating polarization components in a lateral direction. This is due to the orientation of the polarization components caused by the first optical assembly. In the forward direction, all of the polarization components are aligned horizontally when propagating through the shift plate. However, in the rearward direction, the polarization components are aligned vertically.

The nonreciprocal optical device of the first embodiment operates to couple first and second optical fibers to a single third optical fiber. For example, the first and second optical fibers can be positioned adjacent to the second optical assembly, while the third optical assembly is positioned adjacent to the first optical assembly. A light beam from the third optical fiber will be transmitted to the second optical fiber, while a light beam from the first optical fiber will be transmitted to the third optical fiber. However, a light beam from the second optical fiber will not be transmitted to the third optical fiber.

In operation, a forward propagating light beam enters the first optical assembly from a first optical fiber. The light beam is separated into first and second polarization components by the walk-off crystal in the first optical assembly. The first polarization component has a vertical polarization state,

while the second polarization component has a horizontal polarization state. The first polarization component is then rotated 90o by the first optical assembly. The first and second polarization components then exit the first optical assembly and encounter the first focusing lens. The focusing lens initially converges the polarization components to a focal point of the first focusing lens. However, after the focal point, the polarization components begin to diverge. In addition, the relative positions of the polarization components are inverted by the converging and diverging process. Next, the polarization components impinge upon the first compensating lens. Each polarization component is refracted at a flat surface of the compensating lens, such that the polarization components cease to diverge and propagate in parallel with respect to the other polarization component.

Next, the polarization components propagate through the shift plate, which displaces the polarization components in either the positive or the negative x-direction. The polarization components are then caused to converge by the second compensating lens. Again, each polarization component is refracted at a flat surface of the second compensating lens. The polarization components converge to a focal point of the compensating lens and begin to diverge. The polarization components then travel through the second focusing lens, which alters the propagation direction of the polarization component such that the polarization components are again propagating in parallel. The second optical assembly then rotates the first polarization again by 90o and recombines the first and second polarization components. The combined polarization components of the light beam are transmitted to a second optical fiber.

A rearward propagating light beam from the second optical fiber is not transmitted to the first optical fiber. In the rearward direction, the rotation caused by the second assembly is such that the rearward propagating polarization components of the light beam are not displaced by the shift plate. Therefore, the polarization components follow a different propagation path. The two compensating lenses and the two focusing lenses operate on rearward propagating polarization components in the exact opposite manner as on forward propagating polarization component. The second focusing lens now converges the polarization components, while the first focusing lens alters the polarization components to propagate in parallel. In addition, the converging function is performed by the first compensating lens, instead of the second compensating lens.

In a second embodiment of the invention, the second optical assembly, the second focusing lens, and the second compensating lens are removed. Instead, a mirror assembly is placed rearwardly of the shift plate. In this embodiment, a forward propagating light beam emitted from a first optical fiber in an array of fibers is transmitted to an adjacent second optical fiber in the array of fibers in a rearward direction. A light beam emitted from the second optical fiber is transmitted to a third optical fiber, etc.

The mirror assembly includes a mirror and a Faraday rotator. The Faraday rotator operates to change the polarization states of polarization components, so that reflected polarization components are not shifted a second time by the shift plate. The Faraday rotator rotates polarization components by 45o before reflection and again after reflection. The overall effect of the Faraday rotator is a 90o rotation of the polarization components.

In operation, the first optical assembly separates polarization components of a light beam from a first optical fiber and rotates one of the polarization

components by 90o. The polarization components then travel through the first focusing lens, which causes the polarization components to diverge. The compensating lens then adjusts the propagating directions of the polarization components, such that they are propagating in parallel. Next, the polarization components are displaced by the shift plate and travel through the mirror assembly. The Faraday rotator in the mirror assembly rotates the polarization components by 45o. The polarization components are then reflected by the mirror. The polarization components again travel through the Faraday rotator, which rotates the polarization components by another 45o.

Next, the polarization components propagate through the shift plate. However, because the polarization components have been rotated perpendicularly, the polarization components are not displaced by the shift plate. The polarization components then travel through the first compensating lens and first focusing lens. Operating in an opposite manner, the compensating lens converges the polarization components, and the focusing lens then adjust the polarization components such that they are propagating in parallel. In the rearward direction, the first optical assembly rotates one of the polarization components and recombines the polarization components. The recombined polarization components are then transmitted to an adjacent optical fiber in the array of fibers with respect to the first optical fiber.

A method of transferring circulating optical signals from multiple optical fibers utilizes the nonreciprocal optical device in accordance with the invention. First, a light beam is received by an optical assembly of the multi-port optical circulator from a first optical fiber in an array of fibers. The light beam is then separated into polarization components by the optical assembly. Next, one of the polarization components is rotated, such that both polarization components have a common polarization state. The polarization components are then diverged, such that the polarization components are moving away relative to each other. In the process of diverging the polarization components, the polarization components are also inversely projected.

Next, the polarization components are redirected, such that the polarization components are propagating in a parallel manner. After being redirected, the polarization components are laterally displaced. In one embodiment, the polarization components are reflected toward the array of fibers. In addition, the polarization components are rotated perpendicularly. The displaced polarization components are then converged, such that the separation distance of the polarization components is decreasing. Next, the converging polarization components are again redirected to propagate in a parallel manner. Propagating in the parallel manner, one of the polarization components is rotated perpendicularly. Lastly, the polarization components are recombined and transmitted to a second optical fiber.

An advantage of the invention is that fiber-to-fiber coupling efficiency is improved with the use of compensating lens(es). As a result, more fibers may be coupled using the invention. In addition, the optical assemblies utilized in both embodiments of the invention are compact. Still another advantage of the invention is that in the first embodiment of the invention the first and second optical assemblies are physically identical, lowering the cost of fabrication. Finally, the use of the mirror assembly in the second embodiment of the invention greatly reduces the overall size of the device, while maintaining the improved fiber-to-fiber coupling.

DRWDESC:
BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a perspective view of a multi-port optical circulator in accordance with a first embodiment of the invention.

FIG. 2 is a front view of a compensating lens in the multi-port optical circulator of FIG. 1.

FIG. 3 is a side view of the compensating lens.

FIG. 4 is a top view of the compensating lens.

FIG. 5 is an end view of a silicon substrate having V-shaped grooves for precisely aligning four optical fibers.

FIG. 6 is a partial perspective view of the silicon wafer of FIG. 3 having a second silicon substrate to sandwich the optical fibers into position.

FIG. 7 is a top view of the multi-port optical circulator of FIG. 1 with illustrations of propagation paths in the x-direction.

FIG. 8 is a side view of the multi-port optical circulator of FIG. 1 with illustrations of two propagation paths in the y-direction.

FIGS. 9-18 illustrate the operations performed upon polarization components of forward propagating light beams through the multi-port optical circulator of FIG. 1.

FIGS. 19-28 illustrate the operations performed upon polarization components of rearward propagating light beams through the multi-port optical circulator of FIG. 1.

FIG. 29 is a perspective view of a multi-port optical circulator in accordance with a second embodiment of the invention.

FIG. 30 is a top view of the multi-port optical circulator of FIG. 29 with illustrations of propagation paths in the x-direction.

FIG. 31 is a side view of the multi-port optical circulator of FIG. 29 with illustrations of two propagation paths in the y-direction.

FIGS. 32-38 illustrate the operations performed upon polarization components of forward propagating light beams through the multi-port optical circulator of FIG. 29, before being reflected by a mirror at the rearward face of the multi-port optical circulator of FIG. 29.

FIGS. 39-45 illustrate the operations performed upon polarization components of rearward propagating light beams through the multi-port optical circulator of FIG. 29, after being reflected by the mirror at the rearward face of the multi-port optical circulator of FIG. 29.

FIG. 46 is a flow diagram of a method of circulating light beams from and to multiple input/output optical fibers in accordance with the invention.

DETDESC:

DETAILED DESCRIPTION

In FIG. 1, a multi-port optical circulator 10 in accordance with a first embodiment of the invention is shown. The multi-port optical circulator 10 includes a first optical assembly 12, a second optical assembly 14, a pair of focusing lenses 16 and 18, a pair of compensating lenses 20 and 22, and a shift plate 24. The multi-port optical circulator 10 is positioned between two arrays of optical fibers 26 and 28. The array of fibers 26 includes optical fibers 30, 32, 34 and 36. The optical fibers 30-36 are positioned in place by a fiber holder 38. Similarly, the array of fibers 28 includes optical fibers 40, 42, 44 and 46 in a fiber holder 48.

Preferably, the optical fibers 30-36 and 40-46 are thermally expanded core (TEC) fibers having mode field diameters (MFDs) of approximately 20 mu m. Although the fiber arrays 26 and 28 are shown as having four optical fibers, the fiber arrays 26 and 28 may include more or fewer optical fibers. While not critical to the invention, the TEC fiber arrays 26 and 28 have a pitch of 250 mu m.

The optical assembly 12 includes a walk-off crystal 50, an upper half-wave plate 52, a lower half-wave plate 54, and a Faraday rotator 56. The walk-off crystal 50 provides a displacement in the positive y-direction of vertical polarization components of light beams that are propagating in the forward direction, i.e., positive z-direction. The walk-off crystal 50 may be made of rutile (titanium dioxide-TiO2) or yttrium vanadate (YVO4). In addition, inexpensive Lithium Niobate (LiNbO4) may be used to form the walk-off crystal 50. The thickness of the walk-off crystal 50 depends on the type of the optical fibers 30-36 and 40-46, due to the difference in MFDs. Wider MFDs require greater spatial displacement by the walk-off crystal 50.

The upper half-wave plate 52 and the lower half-wave 54 are positioned such that the displaced polarization components propagate through the upper half-wave plate 52, while the horizontal polarization components propagate through the lower-half wave plate 54. The upper half-wave plate 52 and the Faraday rotator 56 operate to provide 90o rotation of polarization components propagating in the forward direction. However, due to the nonreciprocal nature of the Faraday rotator 56, the upper half-wave plate 52 and the Faraday rotator 56 provide 0o rotation for polarization components propagating in a rearward direction, i.e., negative z-direction. Conversely, the lower half-wave plate 54 and the Faraday rotator 56 operate to provide 0o rotation for polarization components of forwardly propagating light beams and 90o rotation for rearwardly propagating light beams.

The focusing lenses 16 and 18 are configured to focus polarization components traveling in either the forward or rearward direction. Preferably, the two focusing lenses 16 and 18 are physically identical converging lenses. While not critical to the invention, the focusing lenses 16 and 18 may provide 1:4 imaging. Preferably, the four lenses 16, 18, 20 and 22 are positioned such that the distance between the focusing lens 16 and the compensating lens 20 is equal to the distance between the compensating lens 22 and the focusing lens 18. In operation, the focusing lens 16 inversely projects polarization components propagating in the forward direction onto the compensating lens 20. The polarization components are projected at angles that depend upon the impinging

position of a polarization component on the focusing lens 16. Similarly, the focusing lens 18 inversely projects polarization components propagating in the rearward direction onto the compensating lens 22. The compensating lenses 20 and 22 receive polarization components from either the focusing lens 16 or focusing lens 18 and refract the polarization components such that the angles caused by the focusing lenses 16 and 18 are countered. The result is that polarization components are propagating in a parallel manner between the compensating lenses 20 and 22, regardless of the propagating direction. Preferably, the compensating lens 20 is positioned at a distance from the focusing lens 16 that is greater than the focal length of focusing lens 16. In addition, the compensating lens 22 is positioned at a distance from the focusing lens 18 that is greater than the focal length of focusing lens 18.

The shift plate 24 is positioned between the compensating lenses 20 and 22. Preferably, the shift plate 24 is a walk-off crystal having a walk-off direction parallel to the x-axis. By properly orientating polarization components of light beams in both the forward and rearward directions, the shift plate 24 provides displacement of polarization components propagating in only one direction.

The second optical assembly 14 also includes a walk-off crystal 58, an upper half-wave plate 60, a lower half-wave plate 62, and a Faraday rotator 64. Preferably, the second optical assembly 14 is structurally identical to the first optical assembly 12, except for the orientation of the second optical assembly 14 with respect to the first optical assembly 12. The second optical assembly 14 is a mirror image of the first optical assembly 12. In other words, the second optical assembly 14 is the first optical assembly 12 that has been rotated 180o about the y-axis. For forward propagating light beams, the Faraday rotator 64 and the upper half-wave plate 60 rotate polarization components by 90o, while the Faraday rotator 64 and the lower half-wave plate 62 provide 0o rotation. Conversely, the Faraday rotator 64 and the upper half-wave plate 60 provide 0o rotation, while the Faraday rotator 64 and the lower half-wave crystal 62 provide 90o rotation for rearward propagating light beams. The walk-off crystal 58 provides displacement in the negative y-direction for vertical polarization components propagating in the forward direction.

Turning to FIGS. 2, 3 and 4, a compensating lens 66 having eight surfaces 68, 70, 72, 74, 76, 78, 80 and 82 on a forward face is shown from various points of view. The upper surfaces 68-74 operate on displaced polarization components of light beams caused by either walk-off crystal 50 or 58. The lower surfaces 76-82 operate on the other non-displaced polarization components. An upper surface and a lower surface form a pair of surfaces that operates on polarization components of a single light beam. For example, if one polarization component of a light beam travels through the upper surface 70, the other polarization component will travel through the lower surface 78. Similarly, surfaces 68 and 76, 72 and 80, and 74 and 82 form the remaining pairs. The surfaces 68-82 are symmetrical about the horizontal centerline 84 and the vertical centerline 86.

The compensating lens 66 can be positioned such that the eight surfaces 68-82 are facing either the positive or negative z-direction. The compensating lens 20 of FIG. 1 is a compensating lens that is facing the positive z-direction. The compensating lens 22 of FIG. 1 is a compensating lens that is facing the negative z-direction. In operation, the compensating lens 66 can refract diverging polarization components of light beams to propagate in a parallel manner. Conversely, the compensating lens 66 can receive polarization components that are propagating in parallel and redirect the polarization components to

propagate in a converging manner.

The fiber holders 38 and 48 of FIG. 1 can be composed of semiconductor substrates. Preferably, the fiber holders 38 and 48 are etched to form V-shaped grooves to properly position the input and output optical fibers 30-36 and 40-46. FIG. 5 illustrates optical fibers 88 positioned on V-shaped grooves 90 that are etched on a substrate, such as a silicon wafer 92. Conventional integrated circuit fabrication techniques may be utilized to form the grooves 90. For example, the grooves may be formed photolithographically, using a mask to define the grooves and using chemical etchant. While not critical, the angle of one of the V-shaped grooves 90 relative to the other wall is preferably 70.5o. The fiber holders 38 and 48 may also include another etched silicon wafer 94 that is affixed to the lower silicon wafer 92 by a layer of adhesive 96, as shown in FIG. 6. The use of an adhesive layer is not critical to the invention. Alternatively, wafer bonding may be used to attach the two silicon wafers 92 and 94.

In FIG. 7, a top view of the multi-port optical circulator 10 is illustrated. Also shown in FIG. 7 are four propagation paths 98,100,102 and 104. The four propagation paths 98-104 may represent paths taken by the displaced polarization components caused by either of the walk-off crystals 50 or 58. However, the four propagation paths 98-104 may also represent paths taken by the other non-displaced polarization components. The reason for the dual representation is that on an x-z plane the two polarization components follow the same path. The only difference between the paths taken by the two polarization components of a light beam is in the y-direction. The difference in paths with respect to the y-axis is illustrated below with reference to FIG. 8.

In a rearward direction, a light beam from any one of the optical fibers 40-46 follows the same referenced propagation paths 98-104. For example, a light beam from the optical fiber 40 would propagate through the optical assembly 14 in a negative z-direction following the propagation path 98. The propagation path 98 is initially located above the other propagation paths 100-104. The focusing lens 18 refracts the light beam, such that the propagation path 98 is now below the other propagation paths. The compensating lens 22 redirects the light beam, such that once again the propagation path 98 is in the negative z-direction.

Propagating through the shift plate 24, the light beam is not affected by the walk-off properties of the shift plate 24. This is due to rotation of the rearward propagating light beam by the optical assembly 14, such that the polarization components are aligned orthogonally to the walk-off direction of the shift plate 24. Therefore, displacing paths 106, 108,110 and 112, illustrated within the shift plate 24, are not applicable for rearward propagating light beams. The light beam is then refracted in a converging manner by the compensating lens 20 and redirected by the focusing lens 16. Following the compensating lens 20 and focusing lens 16, the propagation path 98 of the light beam is back to a location above the other propagation paths 100-104. The propagation path 98 leads to the optical fiber 30. Therefore, light beams from the optical fiber 40 are coupled to the optical fiber 30. Similarly, light beams from optical fibers 42, 44 and 46 are coupled to optical fibers 32, 34 and 36, respectively.

In a forward direction, polarization components of a light beam are affected by the walk-off properties of the shift plate 24. Therefore, the propagation

path of the light beam is shifted by the shift plate 24. For example, a light beam from the optical fiber 36 follows the propagation path 104. However, the light beam is displaced by the shift plate 24, because the operation of the optical assembly 12 aligns the polarization components of the light beam with the walk-off direction of the shift plate 24. The light beam travels through the displacing path 106, and then follows the propagation path 102. Thus, the light beam from the optical fiber 36 is coupled to the optical fiber 44. Similarly, light beams from the optical fibers 34 and 32 are coupled to the optical fibers 42 and 40, respectively. However, a light beam from the optical fiber 30 is not transmitted to any of the optical fibers 40-46. The light beam from the optical fiber 30 is displaced by the shift plate 24 to follow the displacing path 112 that is not aligned with any of the optical fibers 40-46.

FIG. 8 illustrates a side view of the multi-port optical circulator 10. Also shown in FIG. 8 are two propagation paths 114 and 116 with respect to the y-axis. The two propagation paths 114 and 116 represent paths taken by polarization components of any light beam from one of the optical fibers 30-36 and 40-46 through the multi-port optical circulator 10.

In the forward direction, a light beam enters the optical assembly 12 from an optical fiber of the fiber array 26. The vertical polarization component of the light beam is displaced in the positive y-direction by the walk-off crystal 50. Therefore, the vertical polarization component will follow the propagation path 114, while the horizontal polarization component will follow the propagation path 116. The two polarization components are recombined by the walk-off crystal 58 and transmitted to an optical fiber of the array of optical fibers 28. However, as stated above, a light beam from the optical fiber 30 will not be transmitted to any optical fiber of the array of optical fibers 28. Rearward propagating polarization components of a light beam will also follow the same paths 114 and 116 in the same manner.

FIGS. 9-18 illustrate the operation of the multi-port optical circulator 10 on polarization components of light beams from the optical fibers 30-36. For simplicity, only two light beams from the optical fibers 32 and 34 that are propagating in the forward direction, i.e., positive z-direction, are illustrated. Each of the ten figures is an illustration of the relative positions of the polarization components of the two light beams before and after traveling through one of the optical elements in the multi-port optical circulator 10, as viewed from the position of the fiber array 26.

In FIG. 9, a first pair of orthogonal polarization components 118 and 120 and a second pair of orthogonal polarization components 122 and 124 that are about to enter input ports, i.e., windows, at the forward face of the optical assembly 12, are shown. The polarization components 118 and 120 represent a light beam from the optical fiber 32 that is about to enter the input port positioned at location 126. The polarization components 122 and 124 represent a light beam from the optical fiber 34 that is about to enter the other input port positioned at location 128. The other two locations 130 and 132 are positions of ports on the rearward face of the optical assembly 12. Preferably, the locations 130 and 132 are also positions of ports on the forward face of the optical assembly 14. In addition, the locations 126 and 128 preferably represent positions of ports on the rearward face of the optical assembly 14 that are aligned with the optical fibers 42 and 44, respectively. As will be described in detail below, the first light beam from the optical fiber 32 will be transmitted to the optical fiber 40, while the second light beam from the optical fiber 34 will

be transmitted to the optical fiber 42.

The light beams enter the first optical assembly 12, encountering the walk-off crystal 50. As the light beams travel through the walk-off crystal 50, the aligned polarization components 118 and 122 are displaced in the positive y-direction, as indicated by the arrow in the lower left corner of FIG. 9. As shown in FIG. 10, the polarization components 118 and 122 have been displaced to locations 130 and 132, respectively. Next, the polarization components 118 and 122 travel through the upper half-wave plate 52, which rotates the polarization components 118 and 122 in the clockwise direction by 45o, as shown in FIG. 11. The other polarization components 120 and 124 travel through the lower half-wave plate 54, which rotates the polarization components 120 and 124 in the counter-clockwise direction, also shown in FIG. 11. The polarization components 118,120,122 and 124 then travel through the Faraday rotator 56, which rotates all the polarization components 118-124 in the clockwise direction by 45o, as shown in FIG. 12. The overall effect of the upper half-wave plate 52 in conjunction with the Faraday rotator 56 is a 90o rotation of the polarization components 118 and 122 in the clockwise direction. On the other hand, the overall effect of the lower half-wave plate 54 and the Faraday rotator 56 is a 0o rotation o components 120 and 124.

In FIG. 12, the polarization components 118-124 are shown that are about to enter the focusing lens 16. The focusing lens 16 initially refracts the propagating paths of the polarization components 118-124, such that the polarization components 118-124 are propagating in a converging manner. However, the polarization components 118-124 begin to diverge after reaching a focal point of focusing lens 16. When the polarization components 118-124 reach the compensating lens 20, the polarization components 118-124 have been inversely projected onto the compensating lens 20. The compensating lens 20 does not affect the relative positions of the polarization components 118-124. However, the compensating lens 20 does stop the divergence of the polarization components 118-124.

The effect of the focusing lens 16 is shown in FIG. 13, which illustrates the polarization components 118-124 prior to entering the shift plate 24. Four new locations 134, 136, 138 and 140 are shown in FIG. 13. The polarization component 118, which was positioned in the upper left section at location 130 in FIG. 12, is now positioned in the lower right section at location 136. Similarly, the relative positions of the polarization components 120,122 and 124 have been changed from locations 126,128 and 132 to locations 140, 134 and 138, respectively.

From the locations shown in FIG. 13, the polarization components 118-124 travel through the shift plate 24. The polarization components 122 and 124 are displaced to locations 136 and 140, respectively. The polarization components 118 and 120 are displaced to two new locations 142 and 144, respectively. The polarization components 118-124 next encounter the compensating lens 22 and the focusing lens 18. The compensating lens 22 and the focusing lens 18 operate to reverse the effects of the focusing lens 16 and the compensating lens 20. The compensating lens 22 inversely projects the polarization components 118-124 onto the focusing lens 18. The focusing lens 18 refracts the polarization components 118-124 from the compensating lens 22 to a direction parallel to the z-axis. The overall effect of the compensating lens 22 and the focusing lens 18 is to reposition the polarization components 118-124 back to relative positions prior to entering the focusing lens 16.

The polarization components 122 and 124 are now in locations 130 and 126, respectively, as shown in FIG. 15. In addition, the polarization components 118 and 120 are positioned at two new locations 146 and 148, respectively. The polarization components 118-124 then travel through the Faraday rotator 64. In FIG. 16, the polarization components 118-124 have been rotated by 45o in the counter-clockwise direction by the Faraday rotator 64. Next, the polarization components 118 and 122 are rotated by the upper half-wave plate 60 in the counter-clockwise direction by 45o, while the other polarization components 120 and 124 are rotated by the lower half-wave plate 62 in the clockwise direction by 45o, as shown in FIG. 17. The overall effect of the Faraday rotator 64 and the upper half-wave plate 60 is a 90o rotation of the polarization components 118 and 122 in the counter-clockwise direction. On the other hand, the overall effect of the Faraday rotator 64 and the lower half-wave plate 62 is a 0o rotation of the polarization components 120 and 124.

In FIG. 18, the polarization components 118-124 are recombined by the walk-off crystal 58 in front of the fiber holder 48. The polarization component 118 is displaced to location 148 to recombine with the polarization component 120. In addition, the polarization component 122 is displaced to location 126 to recombine with the polarization component 124. As stated above, the optical fiber 42 is aligned with the location 126. Thus, the polarization components 118 and 120 will be transmitted to the optical fiber 42. Furthermore, the location 148 is aligned with the optical fiber 40. Therefore, the polarization components 122 and 124 will be transmitted to the optical fiber 40. In a similar manner, a light beam from the optical fiber 36 will be transmitted to the optical fiber 44.

The rearward propagation of light beams from the optical fibers 40 and 42 to the optical fibers 30 and 32, respectively, is illustrated in FIGS. 19-28. When applicable, the same reference numerals will be used for illustrating the various locations of the light beams along the multi-port optical circulator 10 in the rearward direction, i.e., negative z-direction. Turning to FIG. 19, a rearward propagating light beam having polarization components 150 and 152 exits from the optical fiber 40 and is about to enter the second optical assembly 14 at location 148. In addition, a second rearward propagating light beam having polarization components 154 and 156 exits from the optical fiber 42 and is about to enter the optical assembly 14 at location 126. Shown in FIG. 20, the polarization components 150-156 have traveled through the walk-off crystal 58. Walk-off crystal 58 has displaced the polarization components 150 and 154 in the positive y-direction to locations 146 and 130, respectively, as shown in FIG. 20.

After the walk-off crystal 58, the polarization components 150 and 154 travel through the upper half-wave plate 60, while the polarization components 152 and 156 travel through the lower half-wave plate 62. The polarization components 150 and 154 are rotated by 45o in the clockwise direction by the upper half-wave plate 60, as shown in FIG. 21. However, the polarization components are rotated by 45o in the counter-clockwise direction by the lower half-wave plate 62, as shown in FIG. 21. Next, the polarization components 150-156 are all rotated by 45o in the counter-clockwise direction by the Faraday rotator 64. As shown in FIG. 22, the polarization components 150-156 are now in a vertical position. The polarization components 150-156 then travel through the focusing lens 18.

Identical to the effect of the focusing lens 16 and the compensating lens 20 on forward propagating polarization components, the focusing lens 18 has

inversely projected the polarization components 150-156 onto the compensating lens 22, as shown in FIG. 23. In front of the compensating lens 22, the polarization components 150, 152, 154 and 156 are now at locations 142, 144, 136 and 140, respectively. In FIG. 24, the polarization components 150-156 have traveled through the shift plate 24. The shift plate 24 does not affect any of the polarization components 150-156, because the polarization states of the polarization components 150-156 are orthogonal to the walk-off direction of the shift plate 24.

Next, the polarization components 150-156 travel through the compensating lens 20 and the focusing lens 16. The effect of polarization components traveling through the compensating lens 20 and the focusing lens 16 in the rearward direction is identical to the effect of the compensating lens 22 and the focusing lens 18 on polarization components propagating in the forward direction. The compensating lens 22 inversely projects the polarization components 150-156 onto the focusing lens 16. The polarization components 150-156 then travel through the focusing lens 16. In FIG. 25, the polarization components 150,152,154 and 156 are shown at locations 146, 148, 130 and 126, respectively, in front of the focusing lens 16. The focusing lens 16 has redirected the polarization components 150-156, such that the propagation paths of the polarization components 150-156 are parallel to the z-axis. The polarization components 150-156 then enter the optical assembly 12, encountering the Faraday rotator 56.

In FIG. 26, the polarization components 150-156 have been rotated by 45o in the clockwise direction by the Faraday rotator 56. Next, the polarization components 150 and 154 are rotated by the upper half-wave plate 52 in the counter-clockwise direction by 45o, while the other polarization components 152 and 156 are rotated by the lower half-wave plate 54 in the clockwise direction by 45o, as shown in FIG. 27. The overall effect of the Faraday rotator 56 and the upper half-wave plate 52 is a 0o rotation of the polarization components 150 and 154. On the other hand, the overall effect of the Faraday rotator 56 and the lower half-wave plate 54 is a 90o rotation of the polarization components 152 and 156.

The polarization components 150 and 154 are then displaced in the negative y-direction by the walk-off crystal 50 to locations 148 and 126, respectively, as shown in FIG. 28. As stated above, the optical fiber 30 is aligned with location 148. In addition, the optical fiber 32 is aligned with location 126. Thus, the polarization components 150 and 152 will be transmitted to the optical fiber 30, coupling the optical fiber 40 to the optical fiber 30 in the rearward direction. Similarly, the polarization components 154 and 156 will be transmitted to the optical fiber 32, coupling the optical fiber 42 to the optical fiber 32 in the rearward direction. In a similar manner, the optical fiber 44 is coupled to the optical fiber 34 and the optical fiber 46 is coupled to the optical fiber 36 for rearward transmission of light beams.

The optical elements in the optical assembly 12 can be configured in a number of alternative arrangements without affecting the operation of the first optical assembly. Again, the second optical assembly 14 is structurally identical to the first optical assembly 12. Therefore, the arrangement of the optical assembly 12 will affect the arrangement of the optical assembly 14. First, the walk-off crystal 50 may have a walk-off direction in either vertical direction, i.e., the positive or negative y-direction, to separate the polarization components of a light beam. Second, the upper and lower half-wave plates 52 and 54 can be

positioned in front of the Faraday rotator 56 or rearwardly of the Faraday rotator 56. The only concern is that one polarization component of a light beam travels through the upper half-wave plate 52, while the other polarization component travels through the lower wave plate 54. Preferably, each of the Faraday rotator 56 and the half-wave plates 52 and 54 provides a 45o rotation of polarization components. If the walk-off crystal 50 has a walk-off direction in the positive y-direction, the Faraday rotator 56 and the upper half-wave plate 52 can provide clockwise rotations of a forward propagating polarization component, while the lower half-wave plate 54 provides a counter-clockwise rotation. Alternatively, the Faraday rotator 56 and the upper half-wave plate 52 can provide counter-clockwise rotations, while the lower half-wave plate 54 provides a clockwise rotation. If the walk-off crystal 50 has a walk-off direction in the negative y-direction, the rotations of the upper and lower half-wave plates 52 and 54 are reversed.

Although the multi-port optical circulator 10 is shown coupling eight optical fibers, the multi-port optical circulator 10 can be slightly modified to couple additional optical fibers. The only substantive modification needed to accommodate additional optical fibers is the surface configuration of the compensating lenses 20 and 22. Each two additional optical fibers would require a pair of new surfaces on the compensating lenses 20 and 22.

Turning to FIG. 29, a perspective view of a multi-port optical circulator 160 in accordance with the second embodiment of the invention is shown. The multi-port optical circulator 160 includes an optical assembly 162, a focusing lens 164, a compensating lens 166, and a shift plate 168. The optical assembly 162 is identical to the optical assembly 12 of the multi-port optical circulator 10. The optical assembly 162 includes the walk-off crystal 50, the upper and lower half-wave plates 52 and 54, and a Faraday rotator 56. Also shown in FIG. 29 is an array of optical fibers 170. The array 170 contains four optical fibers 172, 174,176 and 178 in a fiber holder 180. Similar to the multi-port optical circulator 10, the multi-port optical circulator 160 can be modified to accommodate more or fewer optical fibers. The multi-port optical circulator 160 further includes a mirror assembly 182. The mirror assembly 182 is comprised of a Faraday rotator 184 and a mirror 186.

The multi-port optical circulator 160 operates to transmit light beams emitted from one of the optical fibers 172-176 to an adjacent optical fiber. For example, a light beam from the optical fiber 172 will propagate through the multi-port optical circulator 160 and be transmitted to the optical fiber 172. In this configuration, the optical fiber 172 is a unidirectional input fiber and the optical fiber 178 is a unidirectional output fiber. However, the optical fibers 174 and 176 are bidirectional input/output fibers.

In operation, a light beam enters the optical assembly 162 from one of the optical fibers 172-176. The light beam is initially separated into polarization components within the optical assembly 162. The polarization components then travel through the rest of optical assembly 162, the focusing lens 164, the compensating lens 166, and the shift plate 168 in the same manner as polarization components of a light beam traveling through the optical assembly 12, the focusing lens 16, the compensating lens 20, and the shift plate 24 of the multi-port optical circular 10. However, unlike the multiport optical circulator 10, the polarization components are reflected back by the mirror 186 of the multi-port optical circulator 160. Therefore, the polarization components will propagate through the shift plate 168, the compensating lens 166, the

focusing lens 164, and the optical assembly 162 a second time.

The functions of the Faraday rotator 184 of the mirror assembly 182 is to change the polarization states of the polarization components so that the reflected light is not shifted a second time by the shift plate 168. This is achieved by rotating polarization components of a light beam twice by 45o in either the clockwise or the counter-clockwise direction. Because of the nonreciprocal nature of a Faraday rotator, the polarization components are first rotated by 45o when propagating through the Faraday rotator 184 in the forward direction, and further rotated by 45o in the same direction when propagating through the Faraday rotator 184 in the rearward direction.

In FIG. 30, a top view of the multi-port optical circulator 160 is illustrated. Also shown in FIG. 30 are four propagation paths 188,190,192 and 194. Each of the propagation paths 180-194 represents a potential path taken by both polarization components of a single light beam from one of the optical fibers 172-176. Similar to FIG. 7, four displacing paths 196,198, 200 and 202 are shown within the shift plate 168. These paths are taken by only forward propagating polarization components. In a rearward direction, the polarization components are not affected by the shift plate 168, because they have been rotated perpendicularly by the Faraday rotator 184. In this manner, a light beam from one of the optical fibers 172-176 is transmitted to an adjacent optical fiber.

FIG. 31 illustrates a side view of the multi-port optical circulator 160. Also shown in FIG. 31 are two propagation paths 204 and 206 with respect to the y-axis. The two propagation paths 204 and 206 represent paths taken by polarization components of any light beam from one of the optical fibers 172-178 of the array of fibers 170 through the multi-port optical circulator 160. Polarization components of a light beam will follow the paths 204 and 206 in the forward direction as well as in the rearward direction, after being reflected by the mirror 186 of the mirror assembly 182.

FIGS. 32-38 illustrate the operations performed upon polarization components of forward propagating light beams through the multi-port optical circulator 160, before being reflected back by the mirror 186. Again for simplicity, only two light beams from the optical fibers 174 and 176 are illustrated. Each of the seven figures is an illustration of the relative positions of the polarization components of the two light beams before and after traveling through one of the optical elements in the multi-port optical circulator 160, as viewed from the position of the array of fibers 170.

In FIG. 32, a first pair of orthogonal polarization components 208 and 210 and a second pair of orthogonal polarization components 212 and 214 that are about to enter input ports, i.e., windows, at the forward face of the optical assembly 162 are shown. The polarization components 208 and 210 represent a light beam from the optical fiber 174 that is about to enter the input port positioned at location 216. The polarization components 212 and 214 represent a light beam from the optical fiber 176 that is about to enter the input port positioned at location 218. The optical fibers 174 and 176 are aligned with locations 216 and 218, respectively. Location 220 is aligned with the optical fiber 178. The other locations 222, 224 and 226 are positions of ports on the rearward face of the optical assembly 162.

The light beams enter the first optical assembly 162, encountering the walk-off crystal 50. The polarization components 210 and 214 are displaced to locations 222 and 224 by the walk-off crystal 50, as shown in FIG. 33. The polarization components 210 and 214 are then rotated 90o by the upper half-wave plate 52 and the Faraday rotator 56, as shown in FIGS. 34 and 35. However, the polarization components 208 and 212 are rotated 0o by the lower half-wave plate 54 and the Faraday rotator 56.

Next, the polarization components 208-214 propagate through the focusing lens 164 and the compensating lens 166 in the same manner as the polarization components 118-124 through the focusing lens 16 and the compensating lens 20 of the multi-port optical circulator 10. The effects of the focusing lens 164 and the compensating lens 166 on polarization components 208-214 are illustrated in FIG. 36. The polarization components 208, 210, 212 and 214 are positioned at new locations 234, 230, 232, and 228, respectively. The polarization components 208-214 then travel through the shift plate 168, which laterally displaces the polarization components 208-214 in the positive x-direction, as shown in FIG. 37. The polarization components 212 and 214 are displaced to locations 234 and 230, respectively. The other two polarization components 208 and 210 are displaced to two new locations 236 and 238, respectively. In FIG. 38, the polarization components 208-214 have been rotated by 45o in a clockwise direction by the Faraday rotator 184. The polarization components 208-214 are then reflected by the mirror 186.

FIGS. 39-45 illustrate the operations performed upon polarization components of rearward propagating light beams through the multi-port optical circulator 160 of FIG. 29, after being reflected by the mirror 186 at the rearward face of the multi-port optical circulator 160. Again, each of the seven figures is an illustration of the relative positions of the polarization components of the two light beams before and after traveling through one of the optical elements in the multi-port optical circulator 160, as viewed from the position of the fiber array 170.

In FIG. 39, the polarization components 208, 210, 212 and 214 have been reflected by the mirror 186 and are propagating in the rearward direction toward the array of fibers 170. The polarization components 208-214 then travel through the Faraday rotator 184, which further rotates the polarization components by 45o in the clockwise direction, as shown in FIG. 40. Next, the polarization components 208-214 travel through the shift plate 168. However, in the rearward direction, the polarization components 208-214 are not displaced by the shift plate 168, because the polarization states of the polarization components 208-214 are orthogonal to the walk-off direction of the shift plate 168.

Next, the polarization components 208-214 propagate through the compensating lens 166 and the focusing lens 164. The compensating lens 166 and the focusing lens 164 operate on the polarization components 208-214 in the identical manner as the focusing lens 18 and the compensating lens 22 of the multi-port optical circulator 10 on the polarization components 118-124, as shown in FIGS. 14 and 15. After passing through the focusing lens 164, the polarization components 208, 210, 212 and 214 are positioned at locations 218, 224, 220 and 226, respectively, as shown in FIG. 42. The polarization components 208-214 then propagate through the Faraday rotator 56. In FIG. 43, the polarization components 208-214 have been rotated by 45o in the clockwise direction by the Faraday rotator 56. The polarization components 208 and 212 are further rotated by 45o in the clockwise direction by the lower half-wave plate 54, as shown in

FIG. 44. However, the polarization components 210 and 214 are re-rotated by 45o in the counter-clockwise direction by the upper half-wave plate 52.

Lastly, the polarization components 210 and 214 are displaced to locations 218 and 220, respectively, by the walk-off crystal 50. Thus, the polarization components 208 and 210 have been recombined by the walk-off crystal 50 and are transmitted to the optical fiber 176, which is aligned with location 218. Similarly, the polarization components 212 and 214 are recombined and transmitted to the optical fiber 178, which is aligned with location 220. In a similar manner, a light beam from the optical fiber 172 is transmitted to the optical fiber 174.

A method of transferring circulating optical signals from multiple optical fibers utilizing a multi-port optical circulator in accordance with the invention is illustrated as a flow diagram in FIG. 46. First, a light beam is received at step 300 by an optical assembly of the multi-port optical circulator from a first optical fiber in an array of fibers. The light beam is then separated in step 310 into polarization component by the optical assembly. Next, one of the polarization components is rotated, such that both polarization components have a common polarization state. The polarization components are then diverged in step 320 such that the polarization components are moving away relative to each other. In the process of diverging the polarization components, the polarization components are also inversely projected.

Next, the polarization components are redirected in step 330 such that the polarization components are propagating in a parallel manner. After being redirected, the polarization components are laterally displaced, as shown at step 340. In one embodiment, the polarization components are reflected toward the array of fibers as indicated at step 350. In addition, the polarization components are rotated perpendicularly in step 360. The displaced polarization components are then converged in step 370 such that the separation of the polarization components are decreasing. Next, the converging polarization components are again redirected to propagate in a parallel manner. Propagating in the parallel manner, one of the polarization components is rotated perpendicularly. Lastly, the polarization components are recombined in step 380 and transmitted at step 390 to a second optical fiber.

CLAIMS: What is claimed is:

[*1] 1. A method of transferring optical signals comprising steps of:

receiving a light beam at an input port located on a forward face of an optical assembly,

spatially separating said light beam into polarization components within said optical assembly;

diverging said polarization components such that a distance between said polarization components progressively increases;

redirecting said diverging polarization components to propagate in a substantially parallel manner, including a step of refracting said polarization components using a compensating lens having a plurality of flat surfaces, each of said polarization components being refracted by a particular flat surface of said plurality of flat surfaces;

displacing said polarization components in a lateral direction using at least one nonreciprocal optical element;

converging said polarization components such that said distance between said polarization components progressively decreases;

recombining said polarization components to reform said light beam; and

transmitting said light beam via a predetermined optical line.

[*2] 2. The method of claim 1 further comprising a step of reflecting said polarization components back through said optical assembly following said step of spatially separating said polarization components and prior to said step of recombining said polarization components.

[*3] 3. The method of claim 2 further comprising a step of perpendicularly rotating said polarization components, following said step of spatially separating said light beam.

[*4] 4. The method of claim 1 wherein said step of diverging said polarization components includes a step of individually focusing said polarization components to provide transmission of said polarization components.

[*5] 5. The method of claim 1 wherein said step of diverging and said step of converging said separated polarization components further include inverting relative positions of said polarization components with respect to a common point.

[*6] 6. A multi-port nonreciprocal optical device comprising:

separating means positioned to receive a light beam from a first optical line for dividing said light beam into first and second polarization components having propagating directions substantially parallel with respect to a predefined direction;

dispersing means in optical series with said separating means for deflecting said first and second polarization components such that a distance between said first and second polarization components progressively increases with distance from said separating means, said propagating directions of said first and second polarization components being altered to propagating directions non-parallel to said predefined direction;

redirecting means optically coupled to said dispersing means for adjusting said propagating directions of said first and second polarization components back to being substantially parallel to said predetermined direction, wherein said redirecting means is a compensating lens having a plurality of facets, including first and second facets configured to refract said first and second polarization components, respectively, to adjust said propagating directions;

nonreciprocal displacing means that is optically coupled to said redirecting means for laterally shifting said first and second polarization components;

converging means optically coupled to said nonreciprocal displacing means for deflecting said first and second polarization components such that said distance between said first and second polarization components progressively decreases

with distance from said nonreciprocal displacing means; and

recombining means optically coupled to said converging means for combining said first and second polarization components for output via a second optical line.

[*7] 7. The device of claim 6 wherein said compensating lens includes N facets, where N is proportional to a number of optical lines being coupled by said device.

[*8] 8. The device of claim 6 wherein said separating means, said nonreciprocal displacing means, and recombining means are walk-off crystals.

[*9] 9. The device of claim 6 wherein said dispersing means is a converging lens.

[*10] 10. The device of claim 6 further comprising a first nonreciprocal rotator and a second nonreciprocal rotator, said first nonreciprocal rotator being optically coupled to said separating means, said second nonreciprocal rotator being optically coupled to said recombining means.

[*11] 11. The device of claim 10 wherein each of said first and second nonreciprocal rotators includes a Faraday rotator and a half-wave plate.

[*12] 12. A multi-port optical device for signal transmission comprising:

an optical assembly having a forward face with multiple ports to receive and emit light signals from and to a plurality of optical lines, said plurality of optical lines including adjacent first and second optical lines, said optical assembly including a separating means for dividing a light beam from said first optical line into first and second polarization components;

focusing means optically coupled to said optical assembly for individually focusing said first and second polarization components, said focusing means having a diverging effect with respect to directing said first and second polarization components in a diverging manner;

compensating means, in optical series with said focusing means, for directing said first and second polarization components to propagate in a generally parallel manner, said compensating means configured to substantially counter said diverging effect of said focusing means;

reflecting means positioned rearwardly of said optical assembly for redirecting said first and second polarization components back toward said optical assembly; and

nonreciprocal displacing means positioned between said reflecting means and said optical assembly for guiding said first and second polarization components for output via said second optical line.

[*13] 13. The device of claim 12 wherein said compensating means is a compensating lens having a plurality of flat surfaces, two of said plurality of flat surfaces being configured to refract said first and second polarization components by predetermined angles.

[*14] 14. The device of claim 13 wherein said plurality of flat surfaces have N flat surfaces, where N is proportional to the number of said multiple ports in said optical assembly.

[*15] 15. The device of claim 12 wherein reflecting means includes a mirror and a nonreciprocal rotator, said nonreciprocal rotator configured to perpendicularly rotate said first and second polarization components said light beams.

[*16] 16. The device of claim 12 wherein said optical assembly further include a nonreciprocal rotator having a Faraday rotator and a half-wave plate.

[*17] 17. The device of claim 12 wherein said separating means and said nonreciprocal displacing means are walk-off crystals.

[*18] 18. The device of claim 12 wherein said focusing means is a converging lens.

Pat. No. 6064506 printed in FULL format.

6,064,506

<=2> GET 1st DRAWING SHEET OF 5

May 16, 2000

Optical multi-channel separating filter with electrically adjustable photon crystals

INVENTOR: Koops, Hans, Ober-Ramstadt, Federal Republic of Germany

ASSIGNEE-AT-ISSUE: Deutsche Telekom AG, Bonn, Federal Republic of Germany (03)

APPL-NO: 142,405

FILED: Dec. 24, 1998

PCT-FILED: Mar. 3, 1997

PCT-NO: PCT/EP97/01064

SECT-371-DATE Dec. 24, 1998

SECT-102E-DATE Dec. 24, 1998

PCT-PUB-NO: WO97/33192

PCT-PUB-DATE: Sep. 12, 1997

FOR-PRIOR:
Mar. 5, 1996 Federal Republic of Germany 196 10 656

INT-CL: [7] G02B 26#00

US-CL: 359#237; 359#247; 359#298; 359#320; 359#566; 385#40; 385#42; 349#41; 349#49

CL: 359;385;349

SEARCH-FLD: 359#237, 238, 239, 247, 298, 320, 566, 558, 559, 318, 245; 385#39, 40, 41, 42, 44, 45, 46; 349#41, 47, 49

REF-CITED:

U.S. PATENT DOCUMENTS

3,622,792	11/1971	*	Piccininni	359#298
5,260,719	11/1993	*	Maloney	359#320
5,299,054	3/1994	*	Geiger	359#320
5,373,393	12/1994	*	DeJule et al.	359#320
5,432,624	7/1995	*	Black	359#247
5,909,303	6/1999	*	Trezza et al.	359#247

OTHER PUBLICATIONS

Appl. Phys. Letter 67(15), Oct. 9, 1995, pp. 2138-2140-Brown et al.
SPIE vol. 2693-High-Q Photonic Bandgap Resonant Cavities, pp. 170-175-Lin et al, Jan. 1996.
SPIE vol. 2849-Photonic crystals built by 3-D additive lithography . . . pp. 248-256-Koops, Aug. 1996.

PRIM-EXMR: Ben, Loha

LEGAL-REP: Kenyon & Kenyon

CORE TERMS: crystal, optical, photonic, switch, mirror, electrically, geometry, tunable, multipath, transmission, switchable, filter, needle, electrical, dielectric, nonlinear, filled, optical path, two-dimensional, miniaturized, adjustable, schematic, switching, electron beam, deformation, three-path, electrodes, density, packing, recited

ABST:
An optical multipath switch with electrically switchable photonic crystals.

The invention involves the construction of optical multipath switches based on electrically switchable photonic crystals.

A filled photonic crystal, switchable electrically and/or by light, is used as a tunable mirror. By creating selective optical deformations in the photonic crystal, its properties can be influenced in selected areas in terms of transmission capability. This is done preferably by application of a strong electrical field. Light is coupled in and out via fixed photonic mirrors located at an angle to the photonic crystal.

The optical switches of the invention find application in switching networks and serve the purpose of service selection. A very high packing density may be achieved.

NO-OF-CLAIMS: 7

EXMPL-CLAIM: <=9> 1

NO-OF-FIGURES: 5

NO-DRWNG-PP: 5

SUM:

FIELD OF THE INVENTION

The present invention relates to an optical multipath switch composed of electrically switchable photonic crystals.

RELATED TECHNOLOGY

Photonic crystals with band gaps are two-dimensional and three-dimensional dielectric structures in which the propagation of electromagnetic waves, in dependence upon, or independent of, their direction of propagation, is forbidden.

See

1) John, Phys. Rev. Lett. 58, 2486 (1987).

2) Yablonovitch, Phys. Rev. Lett. 58, 2058 (1987).

3) L. McCall, P. w: Platzmann, R. Dalichacuch, D. Smith, S. Schulz, Phys. Rev. Lett. 67, 2017 (1991).

4) M. Leung, Y. F. Liu, Phys. Rev. Lett. 65, 2646 (1990).

5) L. McCall, A. F. J. Levi, R. E. Slusher, S. J. Pearton, R. A. Logan, Appl. Phys. Lett. 60, 289 (1992).

6) Yablonovitch, T. M. Gmitter, Phys. Rev. Lett. 63, 1950 (1989).

7) Yablonovitch, T. M. Gmitter, K. M. Leung, Phys. Rev. Lett. 67, 2295 (1991).

8) K. M. Ho, C. T. Chan, C. M. Soukoulis, Phys. Rev. Lett. 65, 3152 (1990).

Calculations and microwave measurements have shown that cubic face-centred or also two-dimensional cubic arrangements of holes in a dielectric matrix, or of dielectric rods, exhibit such photonic band gaps.

See

9) S. Y. Lin, A. Arjavalingam, "Photonic Bound States in Twodimensional Photonic Crystals Probed by Coherent Microwave Transient Spectroscopy", J. Opt. Soc. Am. B/Vol. 11, No. 10 (1994), 2124.

10) S. Y. Lin, G. Arjavalingham, "Tunneling of Electromagnetic Waves in Twodimensional Photanic Crystals", optics Letters, Vol. 18, No. 19 (1993), 666.

11) D. R. Smith, S. Schulz, S. L. McCall, P. M. Platzmann, "Defect Studies in a Two-dimensional Periodic Photonic Lattice", Journal of Modern Optics, Vol. 41, 2 (1994), 395.

12) C. C. Cheng, A. Scherer, "Fabrication of Photonic Bandgap Crystals", J. Vac. Sci. Technol (1995), Nov./Dec., to be published.

As few as six planes suffice to ensure a high element quality. Two-dimensional and three-dimensional structures of this sort are often termed "photonic crystals." These structures can be generated with high precision by means of nanolithography using electron beam induced deposition. If the cavities of such photonic crystals are filled with nonlinear optical materials or liquid crystals and the entire structure is exposed to a strong electrical field, the optically active lattice constant in a crystal can be set within certain limits by variation of the optical path and hence the filtering effect of the element varied electrically. A fabrication method which employs the extended silylation process with dry etching, indiffusion and subsequent element filling, allows the production of highly integrated components at low cost.

Tunable filters used in optical communications and telecommunications are implemented at present in the form of long optical fibres whose filtering

effect is created by means of Bragg gratings inscribed in special fibres by ultraviolet light.

13) R. Kashyap, "Photosensitive Optical Fibers: Devices and Applications", Opt. Fibres Techn. 1, pp. 17-34 (1994).

14) C. Cremer, H. Heise, R. Marz, M. Schienle, G. SchulteRoth, H. Unzeitig, "Bragg Gratings on InGaAsP/InPwaveguides as Polarization Independent optical filters", J. of Lightwave Techn., 7, 11, 164 (1989).

15) R. C. Alferness, L. L. Buhll, U. Koren, 2.j. Miller, M. G. Young, T. L. Koch, C. A. Burrus, G. Raybon, "Broadly Tunable InGaAsP/InP Buried Rib Waveguide Vertical Coupler Filter", Appl. Phys. Lett. 60, 8, 980 (1992).

16) C. Wu, C. Rolland, F. Sheperd, C. Laroque, N. Puetz, K. D. Chik, J. M. Xu, "InGaAsp/InP Vertical Coupler Filter with Optimally Designed Wavelength Tunability", IEEE Photonics Technol. 4, 4, 457 (1993).

17) Z-M. Chuang, L. A., Coldren, "Enhanced Wavelength Tuning in Grating Assisted Codirectional Coupler Filter", IEEE Photonics Technology Lett., 5, 10, 1219 (1993).

Fabricating such diffraction gratings with high precision over appreciable lengths of several mm to cm is a great technological challenge. Special procedures aim to correct stitching errors which are commonly experienced in electron beam lithography.

18) H. W. P. Koops, J. Kretz, M. Weber, "Combined Lithographies for the Reduction of Stitching Errors in Lithography", Proc. EIPB 94, J. Vac. Sci. Technol. 3 12 (6) (1994), pp. 3265-3269.

19) B. H. Koek, T. Chisholm, A. J. van Run, J. Romijn, "Sub 20 nm Stitching and Overlay for Nanolithography Applications", Jpn. J. Appl. Phys., Vol. 33 (1994), x.-.x.

20) V. V. Wong, J. R. Ferrera, N. J. Damask, H. I. Smith, "Fabrication and Measurement of Highly Coherent Electronbeam-written Bragg Resonators", Abstracts EIPB '95, Scottsdale N3, 331 (1995).

Incorporation of fiber filters and fiber couplers into a macroscopic optical arrangement needs be accomplished using connectors or splices and a hybrid technology. A miniaturization of components is not achievable in this manner. The process called additive lithography uses computer-controlled electron beam induced deposition to build miniaturized photonic crystals, designed as two-dimensional and three-dimensional arrangements of long miniaturized needles, from dielectric materials with nanometer precision.

21) H. W. P. Koops, R. Weiel, D. P. Kern, T. H. Baum, "High Resolution Electron Beam Induced Deposition", Proc. 31st Int. Symp. on Electron, Ion, and Photon Beams, J. Vac. Sci. Technol. B (1) (1988), 477.

These crystals can be inserted direct in the optical path. High-precision computer control of the electron beam in location, time and direction of motion enables the generation of nearly all required crystal geometries and their selective deformation needed to serve the intended optical purpose. Thereby

the optical behaviour of their structure can be tailored to meet the desired needs. By filling the highly refractive needle structures with nonlinear optical material-see

22) M. Eich, H. Looser, D. Y. Ycon, R. Twieg, G. C. Bjorklund, "Second Harmonic Generation in Poled Organic Monomeric Glasses", J. Opt. Soc. Am. B, 6, 8 (1989).

23) M. Eich, A. Sen, H. Looser, D. Y. Yoon, "Corona Poling and Real Time Second Harmonic Generation Study of a Novel Covalently Functionalized Amorphous Nonlinear Polymer", J. Appl. Phys. 66, 6 (1989).

24) M. Eich, G. C. Bjorklund, D. Y. Yoon, "Poled Amorphous Polymers of Second Order Nonlinear Optics", Polymers for Advanced Technologies, 1, 89 (1990)-or by filling the highly refractive needle structures with liquid crystals-see

25) R. Birenheide, M. Eich, D. A. Jungbauer, O. HermannSchonherr, K. Stoll, J. H. Wendorff, "Analysis of Reorientational Processes in Liquid Crystalline Side Chain Polymers Using Dielectric Relaxation, Electro-optical Relaxation and Switching Studies", Mol. Cryst. Liq. Cryst., 177, 13 (1989)-and

by applying a strong electrical field to the filled structure, the optical path in the crystal and hence its properties can be set electrically. This allows the optical transmission characteristic to be shifted finely, and the optical mirror effect, the direction of reflection and possibly the intensity to be varied. Since such elements possess both a very high quality and a very small size (their dimensions are only a few mu m in length, width and height), optical devices and circuits equipped with such filters and mirrors can be implemented with a high packing density.

In addition, solutions exist which use multibeam writing systems with corpuscular beams. These solutions permit optoelectronic devices and integrated optical circuitry to be fabricated most economically by means of additive lithography. See

26) H. Koops, 1974, German Patent Application P 2446 789.8-33, "Korpuskularstrahloptisches-Gerat zur Korpuskelbestrahlung eines Praparates", U.S. Pat. No. 4,021,674, granted on May 4, 1977.

27) H. Koops, 1974, German Patent Application 2 2460 716.7, "Korpuskularstrahloptisches Gerat zur Korpuskelbestrahlung eines Praparates", German patent granted on Dec. 30, 1976.

28) H. Koops, 1974, German Patent Application P 2460 715.6, "Korpuskularstrahloptisches Gerat zur Korpuskelbestrahlung eines Padparates in Form eines Flachenmusters mit mehreren untereinander gleichen Flachenelementen", German patent granted on Oct. 31, 1979.

29) H. Koops, 1975, German Patent Application P 2515 550.4, "Korpuskularstrahloptisches Gerat zur Abbildung einer Maske auf ein zu bestrahlendes Praparat", German patent granted on May 18, 1977.

30) M. Rub, H. W. P. Kcops, T. Tschudi, "Electron Beam Induced Deposition in a Reducing Image Projector", Microelectronic Engineering 9 (1989), pp. 251-254.

31) H. Elsner, H.-J. D6ring, H. Schacke, G. Dahm, H. W. P. Koops, "Advanced Multiple Beam-shaping Diaphragm for Efficient Exposure", Microelectronic Engineering 23 (1994), pp. 85-88.

SUMMARY OF THE INVENTION

It is an object of the present invention to provide a low-loss switch arrangement based on electrically tunable photonic crystals and hence providing a high packing density.

According to the present invention, a two-dimensional or three-dimensional photonic crystal is made from highly refractive dielectric material using of electron beam induced deposition. Photonic crystals with band gaps and one or more narrowband transmission frequency ranges, depending on their design, act as narrowband filters. Calculations and microwave measurements have shown that cubic face-centered or also two-dimensional cubic arrangements of holes in a dielectric matrix, or of dielectric rods, exhibit such band gaps. As few as six planes suffice to ensure a high element quality.

The process called additive lithography is employed to build two- and three-dimensional arrangements of long miniaturized needles from dielectric materials with nanometer precision, direct in the optical path. Owing to high-precision computer control of the electron beam in location, time and direction of motion, process allows the generation of nearly all demanded geometries of crystals and their selective deformation needed to serve the intended optical purpose. This makes it possible to tailor the optical behaviour of the crystal structure to meet the desired needs. Similar structures can also be created by means of nanolithographic procedures and the extended silylation process using dry etching.

By filling the cavities between the needles with nonlinear optical materials and placing the crystal in the electrical field, the arrangement can be electrically tuned within a certain wavelength range and adjusted with high precision. Liquid crystal materials, which serve to fill the structure, permit tunability of the filter over a broad frequency range. By use of liquid crystals as fillers, the filter is operable as a medium-velocity switch. In this fashion, a switchable mirror can be constructed from a crystal filled with nonlinear material.

A switch of the present invention is composed of tunable photonic crystals. These crystals consist of long miniaturized needles which act as high-precision optical mirrors. Such needles serve to generate an optical geometry in which deformations acting as photonic band gaps are created selectively. The cavities between the needles are filled up with nonlinear optical materials or liquid crystals. By appropriate placement of electrodes in the optical geometry, i.e., application of a strong electrical field, the optical transmission characteristic of the entire geometry can be changed up to reflection. Arranging further divided electrodes for separate control of the electrical fields in individual crystal areas of the optical geometry ensures that the optical geometry is at the same time separately variable in individual crystal areas up to reflection. Fixed photonic mirrors are placed directly in the optical path at angles to the individual directions so that the light can be coupled in and out through these mirrors. In this way, an optical switch function is performed by variation of the transmission characteristic of the optical geometry in

combination with the selective coupling out of light via the individual fixed photonic mirrors.

DRWDESC:
BRIEF DESCRIPTION OF THE DRAWINGS

Embodiments of the present invention are elucidated below with reference to the drawings, in which:

FIG. 1 shows a schematic diagram of a tunable photonic crystal which is used as a narrowband filter in a monomode waveguide;

FIG. 2 shows a schematic diagram of a two-path optically adjustable low-loss switch;

FIG. 3 shows a schematic diagram of a three-path optically adjustable low-loss switch;

FIG. 4 shows a schematic diagram of an electrically controllable multipath switch composed of a plurality of three-path switches; and

FIG. 5 shows a schematic diagram of an electrically switchable multipath switch.

DETDESC:

DETAILED DESCRIPTION

FIG. 1 shows a schematic diagram of a tunable photonic crystal which is used as a narrowband filter in a monomode waveguide.

Based on this principle, an optically adjustable low-loss, two-path switch can be designed, for example, as illustrated in FIG. 2. To achieve this, a photonic crystal 2 having a critical geometry acting as a tunable mirror is placed in the optical path between fixed photonic mirrors 4. These mirrors are orientated such that the light is mirrored at an angle of 22.5 degrees and hence hits the geometry of the photonic crystal, which is filled with nonlinear material 3 and acts as a tunable mirror, at a 45 degree angle. If the geometry of the photonic crystal acting as a tunable mirror is switched to transmission direction, the light can pass unrestrictedly. When the geometry of the photonic crystal acting as a tunable mirror is switched to reflection the light is reflected exactly at the fixed mirror, which couples the light into the connecting waveguide 6.

Components of this kind find application in switching networks and serve service selection purposes. The packing density used in this technology is strongly increased because the arrangement composed of mirrors and filter switches is less than 12 mu m long and wide.

If the field plates 5 in the crystal area are structured into four parts, a transmission and reflection can be set in either half by alternate switching of the four crystal quadrants 12, 14, 16, and 18 respectively. In this manner a three-path switch 20 according to FIG. 3 may be realized, the switch having an element with beam paths orientated at 90 degree angles to one other.

By selective switching of transmission and reflection in crystal areas between finer structured field plates, the beam intensity can also be split up under electronic control.

Another possibility for influencing the electrical setting of the switch is to couple additional light into the photonic crystal by means of a controllable light source directed at the crystal filled with nonlinear optical material. This allows fast switching in the upper gigahertz range. In the process, the light can also be directed at the waveguide light guidance plane from the space above or below it. This renders guidance of the switching and the switched light possible in separate planes.

FIG. 4 represents schematically an electrically controllable multipath switch 30 which has several three-path switches 20 formed of photonic crystal areas 22 that are separately tunable electrically and deflection mirrors built from photonic crystals. This arrangement therefore constitutes a cascaded coupler switch which consists of miniaturized switchable four-path directional couplers made from photonic crystals with an adjustable bandpass filter.

FIG. 5 shows the schematic diagram of an electrically switchable multipath switch. The latter encompasses several three-path switches 20 formed of photonic crystal areas 22 which are separately tunable electrically and thus constitute a cascaded coupler switch which consists of miniaturized switchable fourpath directional couplers with an adjustable bandpass filter.

These devices can be combined with similar or different integrated components-for example, mirrors, phase shifters and reflectors--to build integrated circuits for optical signal processing and optical computers with high packing density. It is also possible to fabricate fixed or variable measurement circuits serving to fulfill security functions and to conduct data communication tests on optical fibers.

The present invention represents a novel electrically controllable array of switches designed in integrated technology and with high packing density. The present invention serves to switch voltages and/or light between, or to cross-connect, at least two optical paths. Through the use of high-integration technology, little or no space is required for insertion of the element into the optical paths of, say, a computer circuit.

CLAIMS: What is claimed is:

[*1] 1. An optical multipath switch having electrically switchable photonic crystals, the switch comprising an optical geometry structure including tunable photonic crystals having long miniaturized needles and acting as high-precision optical mirrors, deformations acting as photonic band gaps capable of being generated selectively in the structure;

cavities between the needles being filled with nonlinear optical materials or liquid crystals enabling an optical transmission characteristic of the optical geometry structure to be varied up to reflection by disposing first electrodes in the structure and applying a strong electrical field;

the optical geometry structure being provided with second, divided electrodes for providing separate field guidance in crystal areas for enabling the optical transmission characteristic of the structure to be varied separately in

individual crystal areas up to reflection;

the optical geometry structure being disposed between mirrors of fixed photonic crystals having an orientation so that light hits the optical geometry at a predetermined angle and the light is capable of being coupled in and selectively out via the mirrors.

[*2] 2. An optical multipath switch as recited in claim 1 wherein the optical geometry structure is a tunable mirror switchable between transmission and reflection states, the structure being disposed in an optical path between the mirrors of fixed photonic crystals, the mirrors of fixed photonic crystals being orientated so that the light is mirrored at a 22.5 degree angle and hits the structure at a 45 degree angle, the structure permitting the light to pass unrestrictedly when switched to a transmission state, and, when switched to a reflection state, the structure reflecting the light in the mirrors of fixed photonic crystals, the mirrors of fixed photonic crystals coupling the light into a connecting waveguide, forming a two-path switch with beam cross-connect capability.

[*3] 3. An optical multipath switch as recited in claim 1 wherein the optical geometry structure is disposed between the second, divided electrodes, the second electrodes being divided into four quadrants each having an electrical field separately adjustable so that individual subcrystals are switchable to transmission and reflection states, enabling the photonic crystals to permit the light to pass unrestrictedly or to reflect in one of two directions, so that a function of an electrically switchable three-path switch is performed.

[*4] 4. An optical multipath switch as recited in claim 1 wherein the tunable photonic crystals are divided into a plurality of crystal areas capable of being used either to direct light from a direction to connecting directions or to an adjacent one of the other plurality of crystal areas so that a branchoff to other directions is formed, the optical multipath switch being capable of forming a cascadable switching structure of decadic or other modular arrangement.

[*5] 5. An optical multipath switch as recited in claim 1 wherein the tunable photonic crystals direct light at the mirrors of fixed photonic crystals for orienting the light at 45 degree angles according to a rectangular pattern so that the tunable photonic crystals are geometrically matched.

[*6] 6. An optical multipath switch as recited in claim 1 wherein the tunable photonic crystals are divided by selectively arranged deformations into more than four areas, enabling a fine separation of the areas and a matching of an intensity of deflected light rays and of different directions.

[*7] 7. An optical multipath switch as recited in claim 1 wherein the switch is set electrically by a controllable light source directed at the tunable photonic crystals, enabling additional light to be coupled into the crystals.

Pat. No. 6266176 printed in FULL format.

6,266,176

<=2> GET 1st DRAWING SHEET OF 34

July 24, 2001

Device for optical interconnection

INVENTOR: Anderson, Betty Lise, Gahanna, Ohio
Collins, Stuart A., Worthington, Ohio

ASSIGNEE-AT-ISSUE: The Ohio State University, Columbus, Ohio [02] United States Company or Corporation

APPL-NO: 688,904 (Series 9)

FILED: October 16, 2000

REL-US-DATA:
Continuation-in-part of Ser. No. 9-645,136, August 24, 2000 pending Which is a provisional Application Ser. No. 60-150,889, August 29, 1999

INT-CL: [7] G02F 1#03

US-CL: 359#245; 359#291; 359#619; 359#237; 359#246; 359#247; 359#320; 385#16; 385#18; 385#42

CL: 359;385

SEARCH-FLD: 359#290, 291, 298, 618, 619, 629, 583, 237, 245, 246, 320, 321, 247; 385#2, 14, 16, 18, 42, 40

REF-CITED:

U.S. PATENT DOCUMENTS

4,225,938	9/1980	*	Turpin	708#816
4,474,434	10/1984	*	Carlsen et al.	359#320
4,474,435	10/1984	*	Carlsen et al.	359#320
5,117,239	5/1992	*	Riza	342#375
5,319,477	6/1994	*	DeJule et al.	349#65
5,463,497	10/1995	*	Muraki et al.	359#619
5,465,175	11/1995	*	Woodgate et al.	359#619
5,936,759	8/1999	*	Buttner	359#291
6,064,506	5/2000	*	Koops	359#237

PRIM-EXMR: Ben, Loha

LEGAL-REP: Standley & Gilcrest LLP

CORE TERMS: mirror, beam, spot, input, alpha, ray, cell, plane, modulator, spatial, prism, path, delta, curvature, interconnection, theta, equation, lens, pixel, matrix, fiber, roof, additionally, bounce, slope, array, emerging, polarization, turning, arm

ABST:
The present invention includes optical interconnection devices and optical interconnection systems. The invention also includes machines and instruments using those aspects of the invention. The invention may also be used to upgrade, repair, or retrofit existing machines or instruments, using methods and components known in the art. An optical interconnection device of the present invention utilizes a multiple-pass optical cell. This approach differs from previous approaches in that spatial light modulators are used in a White cell device or other multiple-pass optical configuration. In a spatial light modulator, each individual element typically only has two or three variations used to direct the light. Therefore, precise calibration is not needed. The light simply needs to be directed towards the appropriate arm of the optical cell, which utilizes a self-correcting mirror in order to direct a light stream to the next desired location in the system.

NO-OF-CLAIMS: 51

EXMPL-CLAIM: <=12> 1

NO-OF-FIGURES: 43

NO-DRWNG-PP: 33

PARCASE: This application is a continuation-in-part application of application Ser. No. 09/645,136 filed Aug. 24, 2000 claiming the benefit of Provisional Application Serial No. 60/150,889 filed Aug. 29, 1999.

SUM:

TECHNICAL FIELD OF THE INVENTION

The present invention is in the field of optical interconnection devices, such as those that may be useful in routing information for communications systems.

BACKGROUND OF THE INVENTION

This invention relates to apparatus supporting optical interconnection, such as those that may be useful in the routing of signals in the communications industry. In communications systems such as telecommunications systems, optical signals currently must be downconverted to an electrical signal before being transmitted over long distances. The transmission rate of these electrical signals is much slower than that of optical signals. This conversion is a barrier to a fast Internet system capable of delivering applications requiring significant bandwidth, such as streaming on-demand video and music. It is therefore desirable to use a system that keeps signals in their optical form without having to convert to a slower, less-efficient electrical system.

One area to be addressed is the electronic switches in fiber-optic backbones. Backbones are expensive communications links between major cities. Optical fibers often carry information to central hubs in these major cities, then creating a bottleneck at each hub while all this information waits to be converted into electrons and switched by bulky electronic switches. This conversion process was sufficient when fiber optics carried only one signal

over a limited distance, but electronics now have difficulty keeping up with the newly complex signals.

The industry has turned its attention toward photonic switches. Photonic switches do not require signal downconversion, and are capable of optically directing even complex light streams. Several variations of these photonic switches have been reported. Agilent reportedly uses bubbles to deflect light between crisscrossing glass columns in order to direct light back and forth to the switches. Corning is reportedly investigating liquid crystals to redirect the light streams. Bell Labs is reportedly using tiny micromirrors to direct beams to the appropriate fibers. While these systems are much smaller than the previous switching systems, and may effectively achieve the desired optical switching, they can be very complex. For example, in the Bell Labs device where an array of micromirrors is used to direct beams to the appropriate fiber, each mirror must be accurately calibrated to send a beam to any of the appropriate fibers. The calibration must also take into account any minute variation in position from fiber to fiber, an array of fibers not being aligned in perfect rows and columns.

It is therefore an object of the current invention to create a photonic switching device that is compact in design, relatively simple to setup and operate, and can effectively route multiple complex light streams.

Although described with respect to the field of communications, it will be appreciated that similar advantages of optical routing, as well as other advantages, may obtain in other applications of the present invention. Such advantages may become apparent to one of ordinary skill in the art in light of the present disclosure or through practice of the invention.

SUMMARY OF THE INVENTION

The present invention includes optical interconnection devices and optical interconnection systems. The invention also includes machines and instruments using those aspects of the invention. The invention may also be used to upgrade, repair, or retrofit existing machines or instruments, using methods and components known in the art.

The present invention includes an optical interconnection device utilizing a multiple-pass optical cell and at least one spatial light modulator. In a spatial light modulator, each individual element typically only has two or three variations used to direct the light. In an optical configuration of the present invention, such as a White cell, precise calibration of each individual element is not needed. The light simply needs to be directed toward the appropriate arm of the optical cell, which utilizes a self-correcting mirror in order to direct a light stream to the next desired location in the system.

An optical interconnection apparatus included in the present invention utilizes at least one input light source to generate an array of light beams. A light beam may be of any appropriate wavelength, and it should be understood that an input signal may also comprise any appropriate beam that can carry information and be directed by the elements of the present system. An input mirror may be used to reflect this array to an optical configuration, such as a White cell or equivalent optical device or array, comprising a plurality of optical elements such as mirrors, lenses, gratings, and prisms. These elements are configured so as to define multiple possible light paths for each light

beam in the array. At least one refocusing optical element preferably restricts the divergence of a light beam diverted by the optical elements through at least one of the light paths. A spatial light modulator selects a path from among the light paths for each pass of a light beam through the optical elements. Each beam will undergo multiple reflections off the spatial light modulator. An output plane then receives each light beam emerging from the optical elements. The output plane preferably has two dimensions. The resultant position of each light beam on the output plane is determined in part by the position of the light beam in the input array. The particular light paths traveled by the beam through the optical elements also determine the output location. The emerging light beams may also be placed across a non-planar array to form a non-planar pattern, and the position determined accordingly (although this may make positional determination more difficult).

In another apparatus for optical interconnection included in the present invention, at least one input light source generates at least one individual light beam from at least one direction. An input mirror preferably reflects the beam(s) to a first optical configuration, such as a first White cell or equivalent optical device or array. The first optical configuration is made up of a first plurality of optical elements configured so as to define a plurality of possible light paths for each light beam, and a first spatial light modulator adapted to select a path for each pass of a light beam through the first plurality of optical elements.

The apparatus also utilizes a second optical configuration, such as a second White cell or equivalent. The second optical configuration receives as input any light beams emerging from the first optical configuration. The second optical configuration is made up of a second plurality of optical elements configured so as to define a plurality of possible light paths for each light beam emerging from the first optical configuration, and a second spatial light modulator adapted to select a path from among the light paths for each pass of a light beam through the second plurality of optical elements. The apparatus preferably utilizes an output mirror to reflect each light beam emerging from the second optical configuration. At least one receiving device then receives any emerging light beam. The first and second optical configurations are configured such that a similar period of time is needed for each light beam to pass from the input light source through the optical configurations to the receiving device. The first and second pluralities of optical elements preferably comprise mirrors, lenses, gratings, quarter wave plates, and prisms.

Alternatively, the first and second spatial light modulators may be replaced by a single spatial light modulator. The spatial light modulator is then shared by the two optical configurations, preferably having a portion dedicated to each. The pluralities of optical elements have to be arranged accordingly.

The present invention also includes an optical switching apparatus. The apparatus has as an input source at least one input optical fiber, each input optical fiber adapted to carry an optical signal. An input mirror preferably then reflects the optical signal into a first optical configuration, such as a White cell. The first optical configuration has a first plurality of optical elements configured so as to define a plurality of possible light paths for each optical signal reflected by the input mirror. The first optical configuration also has a first spatial light modulator adapted to select a path from among the light paths for each pass of an optical signal through the first plurality of optical elements. Each beam will undergo multiple bounces off the spatial

light modulator. The apparatus also has a second optical configuration, the second optical configuration adapted to receive as input an optical signal emerging from the first optical configuration. The second optical configuration has a second plurality of optical elements configured so as to define a plurality of possible light paths for each optical signal emerging from the first optical configuration. A second spatial light modulator, or another portion of the first spatial light modulator, then selects a path from among the light paths for each pass of an optical signal through the second plurality of optical elements. A plurality of output optical fibers is then used to receive the optical signals exiting the second optical configuration. The first and second optical configurations are adapted such that a similar period of time is needed for each optical signal to pass from an input optical fiber to an output optical fiber.

DRWDESC:
BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a top view of a standard optical cell configuration on which one embodiment of the present invention is based.

FIG. 2(a) is a front elevational view of the spatial light modulator, along with the input and output mirrors in accordance with the present invention.

FIG. 2(b) is a front elevational view of a bounce pattern in accordance with one embodiment of the present invention.

FIG. 2(c) is another front elevational view of a bounce pattern in accordance with one embodiment of the present invention.

FIG. 2(d) is another front elevational view of a bounce pattern in accordance with one embodiment of the present invention.

FIG. 3 is a top view of the dual-arm cell with a beam splitter in accordance with one embodiment of the present invention.

FIG. 4 is a diagram of an optical configuration using a deformable mirror device spatial light modulator and an appropriate prism in accordance with one embodiment of the present invention.

FIG. 5 is a diagram of a multiple arm version of the deformable mirror device configuration in accordance with one embodiment of the present invention.

FIG. 6 is a diagram of reflected planes in accordance with one embodiment of the present invention.

FIG. 7 is another diagram of reflected planes in accordance with one embodiment of the present invention.

FIG. 8 is a diagram of the object and image planes of a light beam reflected off a DMD element in accordance with one embodiment of the present invention.

FIG. 9 is another diagram of the object and image planes of a light beam reflected off a DMD element in accordance with one embodiment of the present invention.

FIG. 10 is a perspective view of a dual arm cell with an auxiliary mirror in accordance with one embodiment of the present invention.

FIG. 11 is a diagram showing the spots that would appear on the SLM if no pixels are addressed, in accordance with one embodiment of the present invention.

FIG. 12 is a diagram showing a spot pattern that maps 16 inputs to 16 arbitrary outputs in accordance with one embodiment of the present invention.

FIG. 13 is a perspective view of an apparatus of one embodiment of the present invention using a cylindrical lens to focus all spots in the output plane.

FIG. 14 is a perspective view of a dual White cell apparatus of one embodiment of the present invention.

FIG. 15 is a diagram of a spot pattern switched to the output SLM on bounce 4 in accordance with one embodiment of the present invention.

FIG. 16 is another spot pattern diagram in accordance with one embodiment of the present invention.

FIG. 17 is another spot pattern diagram in accordance with one embodiment of the present invention.

FIG. 18 is another spot pattern diagram in accordance with one embodiment of the present invention.

FIG. 19 is a diagram showing spot progression in accordance with one embodiment of the present invention.

FIG. 20 is another diagram showing spot progression in accordance with one embodiment of the present invention.

FIG. 21 is a diagram showing regions of an SLM in accordance with one embodiment of the present invention.

FIG. 22 is another diagram showing regions of an SLM in accordance with one embodiment of the present invention.

FIG. 23 is a diagram of an apparatus of one embodiment of the present invention utilizing a polarizing beam splitter.

FIG. 24 is a diagram showing spot progression in accordance with one embodiment of the present invention.

FIG. 25 is another diagram showing spot progression in accordance with one embodiment of the present invention.

FIG. 26 is a perspective view of a lens array in accordance with one embodiment of the present invention.

FIG. 27 is a diagram of a dual White cell device in accordance with the present invention.

FIG. 28 is a diagram of an arrangement of centers of curvature in accordance with one embodiment of the present invention.

FIG. 29 is a diagram of a spot arrangement in accordance with one embodiment of the present invention.

FIG. 30 is a perspective view showing a dual White cell implemented with a liquid crystal SLM in accordance with one embodiment of the present invention.

FIG. 31 is a diagram showing the possible transitions for the LC-based quadratic cell of FIG. 30.

FIG. 32 is a perspective view showing a dual White cell using a two-position DMD in which there are four White cell mirrors instead of three, in accordance with one embodiment of the present invention.

FIG. 33 is a perspective view of a three-position DMD with three associated White cells in accordance with one embodiment of the present invention.

FIG. 34 is a ray diagram for a roof prism in accordance with one embodiment of the present invention.

FIG. 35 is a ray diagram of a ray test in accordance with one embodiment of the present invention.

FIG. 36 is a diagram of spot position for a light beam in accordance with one embodiment of the present invention.

FIG. 37 is a ray diagram for a right-angled roof prism system of one to embodiment of the present invention.

FIG. 38 is a ray diagram for a dual roof prism system of the present invention.

DETDESC:

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT(S)

In accordance with the foregoing summary, the following presents a detailed description of the preferred embodiment of the invention that is currently considered to be the best mode.

The present invention is based on the traditional White cell and its equivalent optical systems or arrays. FIG. 1 is a diagram of the path of a light beam passing through a White cell. The cell comprises three identical spherical mirrors, all of the same effective radius of curvature. The first mirror 12 is separated from the second 13 and third 14 mirrors by a distance equal to their radii of curvature. The center of curvature 15 of the first mirror lies on the centerline or optical axis 16 and falls between the second and third mirrors. The second and third mirrors are aligned so that the center of curvature 20 of the second mirror 13 and the center of curvature 19 of the third mirror 14 land on the first mirror, for example an equal distance from the optical axis. Light from the second mirror is imaged onto the third mirror, and vice versa. Light is input onto a spot 18 in the plane of, but off the edge of, the first mirror;

the light beam is prepared so that it expands as it goes to the third mirror. The third mirror refocuses the beam to a point on the first mirror. The beam is then reflected to and expanded at the second mirror. The second mirror refocuses the light beam to a new spot 17 on the first mirror. At this point, the light may either exit the cell if the spot is off the edge of the first mirror, or continue to traverse the cell. The beam may traverse the cell a predetermined number of times, depending on the locations of the centers of curvature of the second and third mirrors.

The angle of the input beam may be controlled by an input turning mirror 21, as shown in FIG. 2(a). The angle of the output beam may similarly be controlled by an output turning mirror 22. The input spot of each light beam is shown by a spot 23 on the turning mirrors, and each bounce is shown by a spot on the first mirror 12. A spatial light modulator or other appropriate device may alternatively replace the first mirror. A beam of light may be reflected off the input turning mirror into the White cell, and may traverse the cell until the beam is directed to the output turning mirror, at which point it may exit the cell.

FIG. 3 shows a first modification to the White cell to adapt it to variable applications. A first modification is to change the first mirror 12 from a curved mirror to a flat one and to add a lens 27 of focal length such that the lens-mirror combination is optically equivalent to the mirror it replaces. Next, the flat mirror may be replaced with a spatial light modulator. This particular spatial light modulator may be configured to rotate the direction of polarization of the reflected beam by ninety degrees at any particular pixel that is activated. A polarizing beam splitter 28 may be added, and the distances to the second 13 and third 14 mirrors may be adjusted to maintain imaging. The input light may be polarized in the plane of the figure. The beam splitter may reflect light polarized in the plane perpendicular to the figure but transmit light polarized parallel to the plane of the figure.

A better photonic device may be implemented by next adding a fourth mirror 24 and fifth mirror 25, where these mirrors are identical to the second and third mirrors. There now exist dual cells joined at the beam splitter. A lens 26 length may be added to the other output side of the beam splitter.

If a deformable mirror device spatial light modulator 31 is used, a simple White cell can be constructed as shown in FIG. 4. A prism 32 may be used to direct the light beam through a focusing lens 33 onto the appropriate mirror 34 off the optical axis. FIG. 5 also shows that another prism 37 may be introduced to direct light from the deformable mirror device spatial light modulator 31 through a refocusing lens 38 onto the other off-axis mirror 39 in the dual-arm configuration.

A prism such as 32 and its adjacent lens such as 33 may be replaced with a single lens that is appropriately tilted or decentered or both.

Materials and Methods

Imaging Conditions. An analytical description of one arm of the White cell is presented. The configuration to be described is shown in FIG. 3. At the right of the figure, a White cell spherical mirror B (14) is shown below the axis and a White cell mirror C (13) above the axis. The center of curvature of White cell mirror B is a distance [delta] <1> above the optical axis (shown by the dotted

line in the figure passing between mirrors B and C). The center of curvature of Mirror C is a distance [delta] <2> below the optical axis. To the left of the lower White cell mirrors is lens f127 with focal length f<1>. Adjacent to it is the polarizing prism 28 represented by a cube of glass of side d, and next to that is a flat mirror perpendicular to the optical axis representing the SLM. To present the analytical description of the imaging requirements, optical ray matrices are used. These matrices operate on a column vector <=13> Get Mathematical Equation

where y, n, and p<y> refer to the projection of a ray on the y-z plane. The vector element y represents the displacement of the ray from the optical (z) axis at some value of z. The element p<y> represents the slope of the ray at that point and n is the refractive index in the region. The third matrix element "1" is used in representing a tilted spherical mirror as will be shown later. A similar analysis could be used with y replaced by x and p<y> replaced by p<x> for the projection of the ray on the x-z plane. 3 x 3 ray matrices are used because they will be useful in representing the tilted spherical mirrors. Three ray matrices are used. The first is the matrix T(d, n), representing a translation through a material of refractive index n by a distance d in the axial direction. <=14> Get Mathematical Equation

The second is the matrix L(f) representing a thin lens of focal length: <=15> Get Mathematical Equation

The thin lens matrix is identical to that of a spherical mirror of focal length f with its center of curvature on the axis.

A last matrix represents a spherical mirror tilted so that a line from the intersection of the mirror and the optical axis to the center of curvature, point CC, makes an angle [theta] with the optical axis. A ray comes from the lower left with slope p<y1> reflecting off the mirror at point P and leaving with slope p<y2>. Line CCP is drawn from point P through the center of curvature. There are two lines parallel to the axis, one through the center of curvature and one through point P. Line CCP makes angle [alpha] <1> with the incoming ray and angle [alpha] <2> with the reflected ray. The-center of curvature is a distance [delta] above the optical axis, and point P is a distance y above the optical axis and a distance y' above point CC.

There are five equations to be addressed for this situation. Since the angle of incidence equals the angle reflection, [alpha] <1> = [alpha] <2>. For small angles [alpha] <1> = p<y1> - (y'/R) and [alpha] <2> = p<y2> + (y'/R). Also, y = y' + [delta] and [delta] = [theta] R = 2 [theta] f, where f is the focal length of the mirror. Combining these equations to eliminate [alpha] <1>, [alpha] <2>, y', and R, gives p<y2> - [theta] = p<y1> + [theta] - y/f, the equation relating p<y1>, the ray slope before reflection off the spherical mirror with p<y2>, the ray slope after reflection. This leads to the ray matrix M(f, [theta]): [theta] [theta] <=16> Get Mathematical Equation

To use these matrices in practice, one may identify the translations, thin lenses, and mirrors encountered as a ray traverses an optical system. The associated matrices may then be multiplied together to represent the effect of the optical system on the ray. Call the product matrix S. There then results a matrix equation representing the ray slope-index products at the input and output n<1>p<y1> and n<2>p<y2> and the displacements of the ray from the axis at the input and output, y<1> and y<2>: <=17> Get Mathematical Equation

This represents three simultaneous equations. For example, the first such equation is y<2> = Ay<1> + B n<1>p<yl> + G. This equation nicely relates the input and output ray positions. The requirement that there be imaging between the input and output planes is that matrix element B = 0. That requirement allows solving for the desired distances or focal lengths.

To return to the optical system, there are four requirements for proper operation. The first requirement is that Mirror B be imaged onto Mirror C so that no light will be lost by rays starting from Mirror B and missing Mirror C. To establish this requirement, the system matrix S(B, C) is calculated for rays traversing from Mirror B to Mirror C. It is S<(B,C)> = T(d, 1)L(f<1>)T(2d<1>, n<1>)L(f<1>)T(d, 1). Inserting d, d<1> and f<1> in the appropriate matrices and multiplying the matrices together yields: [][[][]][][[]][] <=18> Get Mathematical Equation

The requirement that Mirrors B and C be conjugates then is that matrix element B be zero:

2[(1 - [d/f<1>])(d + (d<1>/n<1>)(1 - [d/f<1>]))] = 0.

This is used to give the desired focal length for lens f<1>. There are two solutions: f<1> = d and f<1> = d/(1 + [n<1>d/d<1>]). These solutions represent symmetric and anti-symmetric ray patterns about the SLM. In the first solution a point on Mirror B has an image at infinity which gives an image on Mirror C with a magnification of - 1. In the second solution a point on Mirror B has an image on the SLM. This also gives an image on Mirror C with a magnification of + 1. The first solution works very nicely for this situation. This puts Mirrors B and C in the focal plane of lens f1. The same analysis applies to Mirrors E 25 and F 24 and lens f226 as shown in FIG. 3. Mirrors E and F are in the focal plane of lens f2.

The second requirement is that Mirrors E and F be images of each other.

Considering requirements three and four that a point on the SLM be imaged back onto itself through each cell, take f to be the focal length of mirror B. The system matrix for that case is given by S = T(d<1>n<1>)L(f<1>)T(d,1)L(f, [theta])T(d,1)L(f<1>)T(d<1>,n<1>). Multiplying the appropriate matrices together and putting f<1> = d as required by the first imaging condition results in [] <=19> Get Mathematical Equation

The imaging condition is then B = 0 = 2(d - [d<1>/n<1>]) - (d<2>/f), or f = d/[2(1 - [d<1>/n<1>d])]. This equation allows predicting the required focal length for the spherical mirrors.

The equation also has some interesting implications leading to physical meaning. For the first one, consider the image of the center of curvature of Mirror B through lens f1. The radius of curvature of Mirror B is 2f and the distance of its center of curvature from lens f1 is d - 2f. Then the distance of the image from the center of curvature, call it d<cc>, is given by 1/d<cc> + 1/(d - 2f) = 1/f<1>. Eliminating f in these equations and simplifying results in d<cc> = d<1>/n<1>. That is, the image of the center of curvature of Mirror B lies on the SLM surface. The image of the center of curvature of mirror B on the SLM can be called the center of curvature point.

To find out where on the SLM surface the center of curvature point is located, look to the magnification. The y value of the image of the center of curvature point, call it y<cci> is given by the y value of the center of curvature itself, y<cco>, times the magnification, or y<cc> = y<cco> x magnification = 2f [theta] x (- image distance/n<1>)/(object distance) = 2f [theta] x [- d<1>/(n<1>[d - 2f])]. Using a previous equation for 2f and simplifying gives y<cc> = [theta] d, which has a very nice interpretation. If a line is drawn from the intersection of the optical axis with Mirror B through the center of curvature of Mirror B, then the intersection of that line, extended if necessary, with lens f1 is a distance [theta] d from the axis. The projection of that intersection onto the SLM gives the center of curvature point.

There is a further interpretation in terms of point sources on the SLM that are imaged back onto the SLM. Writing the first linear equation for the system matrix gives y<2> = - y<1> + 2 [theta] d. Here, y<1> is the location of a point source on the SLM and y<2> is the location of its image after the light from the source has passed through lens f1, been reflected off Mirror B and passed back through lens f1. Defining [delta] = [theta] d and rewriting this equation gives (y<2> - [delta]) = - (y<1> - [delta]). This is interpreted in terms of a distance [delta] . The interpretation is that the image formed by Mirror B of a point on the SLM is as far above the center of curvature image as the object is below the center of curvature point.

The behavior in the x direction is identical, with the exception that Mirror B is tipped only in the y direction so that [theta] = 0. The x equation equivalent is x<2> = - x<1>. Since the center of curvature point is on the y axis, an image of a point source from the center of curvature is as far from the source point as the object was, but on the opposite side in both the x and y directions. To find the image of a point source on the SLM, one can merely reflect about the center of curvature point.

Deformable Mirror Device SLM. To derive a ray matrix for a particular situation two equations are needed, one showing how the distance of a ray from the axis changes as the ray moves through the object, and the other showing how the ray slope changes. Some pixel-mirrors of the DMD are oriented with their normals at + [theta] and some at - [theta] . The surface of the DMD may be defined as a vertical line (y direction) intersecting the center of each pixel so that part of the pixel is behind the surface and part is in front of it. A ray can enter from the right with an angle p<o> and intersect the pixel at a distance y above the center of the pixel, then be reflected off the pixel. At the point the ray intersects the pixel, it is a distance d = ytan [theta] behind the surface. In going from the surface to the pixel, the height of the ray has increased a distance d tan p<o>, = y tan [theta] tan p<o>. After reflection from the pixel, the ray again passes through the surface. In doing so, the height has further increased a height dtan(p<o> + 2 [theta]) = ytan [theta] tan(p<o> + 2 [theta]). The height has changed by a total distance [DELTA] y = ytan [theta] [tan(p<o>) + tan(p<o> + 2 [theta])].

The ray matrices deal with paraxial rays so that p<o> < < [pi] , and [theta] = 10 [degrees] < < 180 [degrees] , also a small angle. Putting the tangent of the angle equal to the angle, the increase in height [DELTA] y = 2y [theta] ([theta] + p<o>). The net result of all these steps is that the increase in height is proportional to the product of small angles and can be neglected. Thus the first matrix ray equation relates the input y value, y<o>, with the output

y value, y<1>, as y<1> = y<o>. The second equation is the one for the slopes. Using the law of reflection, the incident slope, p<o>, and the reflected slope, p<1>, are related as p<1> - [theta] = p<o> + [theta] , or p<1> + p<o> + [theta] . Combining these equations into a 3 x 3 ray matrix yields the ray matrix for the DMD: [theta] <=20> Get Mathematical Equation

There is an addendum that can be mentioned, where the discussion could also apply to reflection off a tipped plane mirror if extending the edge of the pixel-mirror. Thus, the matrix equation also applies to a tipped plane mirror if the tip angle is small. If the tip angle is not a small angle, however, then the approximation does not hold and there will be an increase in distance from the axis.

Next, a prism with a small angle is considered. A prism with its apex pointing down can be considered. The refractive index of the prism material is n. The two large sides make small angles [alpha] <o> and [alpha] <1> with the vertical. A ray with slope p<o> and height y<o> can come in from the right, be refracted at the interfaces, and leave. Since the angles between the surfaces and the vertical are small, arguments like those used previously for the mirror can be used to show that the vertical displacement in crossing the prism can be neglected. The first matrix equation is then y<1> = y<o>. Snell's law can be used to derive the equation for the change of slope. The entering ray has a slope p<o>. The slope of the ray exiting the surface is p'. The angle between the ray entering the surface and the normal is p<o> - [alpha] <0>. Similarly, the angle between the ray exiting the surface and the normal is p' - [alpha] . Snell's law is then sin(p<o> - [alpha] <o>) = n sin(p' - [alpha] <o>), or using the small angle restriction, np' = p<o> + 2(n - 1) [alpha] <0>. A comparable equation can be written for the ray as it exits the left-hand surface: p<2> = np' + (1 - n) [alpha] <1>.

Eliminating p' and defining the prism angle, [alpha] = [alpha] <o> - [alpha] <1>, we have the equation for the change of slope by the prism, p<2> = p<1> + (n - 1) [alpha] . The ray matrix for the small angle prism is then: [alpha] <=21> Get Mathematical Equation

Discussion

A dual White cell is shown in FIG. 3 connected by a polarizing prism beamsplitter. The mirror in the optical spatial light modulator 12 and spherical mirrors B (13) and C (14), combined with lens f1 (27), constitute one White cell, hereafter referred to as Cell I. The mirror in the SLM and spherical Mirrors E (24) and F (25), combined with lens f2 (26), constitute a second White cell called Cell II. The distances between the SLM and Mirrors B and C are the same, and the distances for light reflected off the polarizing beamsplitter going to Mirrors E and F are the same. The distance from the SLM to Mirrors E and F is also the same as the distance from the SLM to Mirrors B and C. In operation, a light beam bounces from the SLM to one of Mirrors B, C, E and F and back again on each traverse of the cell.

The polarizing beamsplitter and the SLM determine which cell the beam goes to on each pass. The polarizing beam splitter transmits light of one polarization, say the plane of the figure, and reflects light of the polarization perpendicular to the plane of the figure. If the light starts out going to Mirror B with polarization in the plane of the figure and the SLM does not change the polarization, it is then reflected back and forth between the SLM

and Mirrors B and C. Conversely, if the light starts towards Mirror E with polarization perpendicular to the plane of the figure and the SLM does not change the polarization, it will continue to reflect between the SLM and Mirrors E and F. The path of a beam can be changed from one cell to the other by using the SLM to rotate the plane of polarization as the beam bounces off the SLM.

Five possible imaging conditions are examined. First, the focal length of lens f1 is chosen to image Mirror B onto Mirror C and vice versa. Second, similar to the first condition, the focal length of lens f2 is chosen to image Mirror E onto Mirror F and vice versa. This requirement may be met by placing Mirrors B and C in the right hand focal plane of lens f1 and by placing Mirrors E and F in the focal plane of lens f2. The third condition is that Mirror B should be imaged onto Mirror F, and Mirror C should be imaged onto Mirror E. The requirement that Mirrors B and C be in the focal plane of lens f1 together with the requirement that Mirrors E and F be in the focal plane of lens f2 also satisfies this condition.

The last two imaging conditions are also comparable. The fourth condition is that the focal lengths of Mirrors B and C are chosen so that, in conjunction with lens f1, Mirrors B and C image a small spot of light on the SLM back onto another small spot on the SLM. The last condition is that the focal lengths of Mirrors E and F are chosen so that, in conjunction with lens f2, a small spot of light on the SLM is again imaged back onto the SLM.

In operation, a point of light starts on a small mirror next to the SLM called a turning mirror. The light is directed towards Mirror B. Suppose the light is polarized in is the plane of FIG. 3 so that it is not reflected off the polarizing beam splitter. Mirror B images the spot back onto the SLM. In one scenario, the light is reflected off the SLM and imaged by lens f1 onto Mirror C, which images it to a different spot on the SLM. It then goes to mirror B, which again images it onto the SLM. The light bouncing back and forth forms a sequence of spots on the SLM.

If the polarization is changed by the SLM to be perpendicular to the plane of the figure, the light bounces in a similar fashion back and forth between Mirrors E and F and the SLM. The plane of polarization of the light can be changed at any bounce off the SLM so that any combination of paths in cells one and two can be chosen.

Considering the exact locations of the spots of light on the SLM, there are various configurations, depending on the locations of the centers of curvature of Mirrors B, C, E and F and also depending on the size of the SLM. The centers of curvature of Mirrors E and F may be located at different points than those of Mirrors B and C. Reference will only be made to the centers of curvature of Mirrors B and C in describing the spot patterns for simplicity.

FIG. 2(b) is a view of the SLM looking at it from lens f1, showing one possible spot pattern. The SLM is assumed to have a square shape. Also shown are two mirrors below the SLM, the input turning mirror on the right and an output turning mirror on the left. A spot is introduced into the cell at a distance of - 2m [delta] from the x-axis, where m is an integer related to the number of times the light is re-imaged on the SLM. The projections of the centers of curvature of Mirrors B and C are taken to be +/- [delta] from the horizontal axis.

The point of light on the input mirror is conditioned, as mentioned previously, to M be traveling toward Mirror B. That spot is imaged to a new point on the SLM located opposite the center of curvature of Mirror B and an equal distance from the center of curvature. The position of the input spot is (x_0, y_0) where $y_0 = -2m\delta$. The point image is at a location opposite the center of curvature of Mirror B. To find that location the signs of both coordinates are reversed and in addition 2 δ is subtracted from the y coordinate. If the light were being imaged by Mirror C, the signs of the coordinate would be reversed and 2 δ added. The result is

$$(x_1, y_1) = (-x_o, y_o - 2\delta) = (-x_o, +2\delta(m-1)).$$

The light is then reflected back and re-imaged by Mirror C. The point image is opposite the center of curvature of Mirror C and an equal distance from it. The location is then at

$$(x_2, y_2) = (-x_o, -y_o + 4\delta) = (-x_o, -2\delta(m-2)).$$

As the process continues, the light alternately bounces off Mirror B and C and is re-imaged. Locations of successive spots are designated as (x_n, y_n) at the nth re-imaging. These spot locations are given by

$$(x_n, y_n) = ((-1)^n x_o, (-1)^n (y_o - 2n\delta)) = ((-1)^n x_o, (-1)^n + 2\delta(m-n)).$$

In this example, the point images form two vertical lines of spots at $\pm x_o$. The point images are indicated with filled circles. The horizontal coordinate of the points alternates to the left and right of the center. As the image number n increases, the spots also alternate above and below the axis, first moving successively toward the axis and then away. The process ends when the spot location falls off the mirror and winds up on the output turning mirror.

It is possible to introduce a second input spot, as shown by the square in FIG. 2(c). It also is imaged across the centers of curvature of Mirrors B and C and creates a unique spot pattern that does not conflict with the previous input beam. The entire input turning mirror may be covered with a two-dimensional array of input spots, as indicated by the additional shapes.

If the beams are always directed to go to Mirrors B and C, the spots will trace out their individual patterns and appear in their appointed locations on the output turning mirror. Next, passes to Mirror E are allowed. Mirror E is aligned with its center of curvature displaced from the line containing the centers of curvature of Mirrors B and C as shown in FIG. 2(d). When a light beam is switched such that it goes to Mirror E instead of Mirror C, the next image spot appears in the same row but in a different column. In the figure the beam is sent to Mirror E one time. It starts out going to B, then goes to E. The spot then appears in a new column. The light then goes to Mirror B again, and appears in a new column on the left side. When the light goes to Mirror C and B for the rest of its bounces, it will trace out the pattern of spots indicated by the filled circles. Note that the output beam exits the cell on a different output turning mirror. The open circles represent the spot pattern that would have resulted had the m never gone to Mirror E.

Instead of a specific situation where the centers of curvature of mirrors B and C are equidistant from the optical axis, a more general situation can be discussed. There, the centers of curvature of the mirrors are on the y-axis. The center of curvature of Mirror B is at location y<B>. The center of curvature of Mirror C is a distance 2 [delta] above it. The input spot is at location x<o>, y<o>. The expression for the location of spot n is (x<n>, y<n>) = ((- 1)<n>x<o>,(y<B> + [delta]) + (- 1)<n>(y<o> + 2 [delta] n)), where y<B> + [delta] is the location of the point midway between the two centers of curvature. The equation still gives two columns of spots parallel to the line between the centers of curvature, the y-axis. The spots alternate from one column to the other as n increases. In general, a distance 4 [delta] separates the spots in a given column. The vertical positions of the spots in one column are, however, not identical with those in the other column. They depend on the y value of the location of the input spot. The equation reduces to the previous equation when y<B> = - [delta] . Two special cases present themselves. For simplicity, the origin is taken midway between the centers of curvature so that y<B> + [delta] = 0. In the first case y<o> is an even integer times [delta] , or y<o> = n<e> [delta] (n<e> even). This is the situation for n = 6. Then the y values of the spots in one column are midway between the y values of the spots in the other column. The input spot is on the bottom turning mirror and the output spot is on the top turning mirror as in FIG. 2(a). There are m - 1 reflections off the SLM.

The second specific case arises when yK is an odd multiple of [delta] , y<o> = n<o> [delta] (n<o> odd). Then for each spot in one column there is a spot opposite it in the other column. The input spot is on the bottom turning mirror and so is the output spot. There are still n - 1 spots on the SLM.

A Deformable Mirror Device spatial light modulator (DMD) is also used in the present invention. The DMD has the potential advantages of higher information density and faster speed. But it also has some associated problems that have to be addressed. The DMD is a pixilated spatial light modulator. That is, the reflecting lis surface is divided into incremental image areas. Each image element has a mirror surface that can be independently rotated to two positions, for example making angles of +/- 10 [degrees] with the surface. The elements can modulate the direction of the reflected light by changing the input direction to one of two output directions. It does this element by individual image element. The direction change can be transformed into an amplitude change by directing the reflected light through an aperture or directing it to something blocking it. Pulsing the mirror between transmitting and blocked states, at a rate faster than eye or detector response, can also change the average observed amplitude.

Imagine a cut through the DMD surface, where the individual mirrored image elements are shown as in FIG. 5. Some are rotated in one direction, the remaining mirror elements in the other possible direction. The angle, [theta] , of tip is +/- 10 [degrees] on presently available devices so that light incident normal to the plane of the DMD is reflected from a given image element at +/- 20 [degrees] . The reflective image elements or pixels are currently square, 16 [mu] m on a side with a spacing of 17 [mu] m between centers. There is a hole in the center of each image element roughly 6 [mu] m in diameter. The pixels rotate about a diagonal. The light incident perpendicular to the paper is reflected in the +/- x direction.

The DMD presents an interesting pattern on reflection. To see this, compare it to a flat mirror 47 as shown in FIG. 6. The intersection of the mirror

surface with the x-z plane makes an angle a with the x-axis. A plane wave travelling in the z direction enters at the bottom, is reflected off the mirror, and exits to the lower left. This is in the near field of the mirror. A continuous reflected wavefront results as expected. Considering a plane wave reflected off the DMD 48, as shown in FIG. 7, the image element mirror surfaces are all oriented in the same direction for simplicity. The mirror surfaces do not form a continuous surface as in the case of the extended plane mirror. As a result the field reflected off the DMD is a discontinuous set of wavefronts all travelling in the same direction but with some lagging behind. The discontinuous set forms an "average" plane parallel to the plane of the DMD. However, this average plane is not perpendicular to the direction of propagation of the reflected light.

The fact that the elements of the DMD do not lie in one continuous surface makes it more difficult at times to image the DMD in reflected light. The difficulty is shown in FIG. 8. A DMD 49 at the left is normally illuminated with a beam from the right. The reflected light is imaged with a lens 50. Neither the object plane nor the image plane is perpendicular to the direction of propagation of the light leaving the DMD. Indeed the object plane and image plane are parallel only if the magnification is unity or if the lens is rotated to be parallel to the object plane as shown in FIG. 9. The main problem is that the object and image planes are not perpendicular to the direction of propagation.

If the direction of the light were reversed so as to be incident on the DMD 49 at an angle and leaving it perpendicular to the surface, as shown in FIG. 9, then there would be no problem. That is the way projectors using the DMD operate. For application in a White cell, however, it may be necessary to have light approaching the SLM from both directions.

One way to remedy the problem of the object plane and image plane not being perpendicular to the direction of propagation is to use an associated prism to change the direction, as shown in FIG. 4. The DMD is illuminated with light normal to its surface as before, and a prism is placed in the reflected beam. The directions and the angles of the prism have been adjusted to remove the angular offset of the DMD. The lens is then used in a normal fashion.

The effect of the prism can be demonstrated analytically. To do this, a ray matrix description is utilized. A ray with slope po incident on a DMD mirror/pixel leaves the pixel with slope p<1>. The 3 x 3 ray matrix for the DMD whose mirror elements are tipped by +/- [theta] is given by [theta] <=22> Get Mathematical Equation

The first of the three linear equations represented by the matrix equation shows that upon reflection the position of the ray remains constant and the second linear equation shows that the slope changes direction by +/- 2 [theta] . Similarly, it has been shown that for the prism the ray matrix for a prism of small angle [alpha] and index n<1> is given by

[alpha] <=23> Get Mathematical Equation

Return to the situation in FIG. 4 where a DMD is on the left so that the light is reflected upward, translates a distance d and passes through the prism. The effect of the angle on the DMD can be cancelled. To find the conditions, multiply the matrices for the DMD, the translation and the prism and accept

that the product be equivalent to that for the translation by itself. Thus, [alpha] [theta] [theta] [theta] [alpha] <=24> Get Mathematical Equation

It is seen by taking the product that the angular offset of the DMD is cancelled if [alpha] = 2 [theta] /(n - 1). The horizontal axis is then translated upward in the y direction by a distance y<d> = + 2d [theta] . The axis is selected by choosing for the position and input slope y<o> = 0 and p<o> = 0. Using these in the previous equations, we find the output position is y<1> = + 2d [theta] . This is reasonable because the axis has been raised by a distance y<d> = 2d [theta] in translating a distance d. To compensate for this, set y<1> = y<2> - y<d> = y<2> - 2 [theta] d. This affects only the top line in the above equation. The result is the following matrix equation. Note that the equation has the form of a simple translation by a distance d. <=25> Get Mathematical Equation

Thus, with the redefined axis the prism compensates nicely for the angular deflection of the DMD.

The equivalent of the Dual White Cell with unequal arms using the DMD is shown in FIG. 5. There the DMD 31 is at the left and to the right of the DMD are lens f136 and spherical Mirror C 35. There are two paths, depending whether a given pixel reflects light up or down. For light reflected downwards there are prism P<1> 37, lens f238 and Spherical Mirror B 39. For light reflected upward, there are Prism P<2> 32, lens f'<2> 33 and Mirror M 34. The prisms counteract the angular effects of the DMD as described. Of the two sets of conditions, the SLM-imaging conditions, and the light-conserving conditions, it is simpler to consider the light-conserving conditions first. The light-conserving conditions are that Spherical Mirrors B, C, and M be imaged onto each other and no light is lost going around the outsides of Mirrors B, C or M. This is accomplished by placing Mirrors B, C, and M in the focal planes of Lenses f<2>, f<1>, and f'<2> respectively. The curvatures of Mirrors B, C, and M are all chosen so that in conjunction with lenses f<2, f><1>, and f'<2> the DMD is imaged back onto itself. As has been shown, images of the centers of curvature of Mirrors B, C and M through Lenses f<1>, f<2>, and f'<2> lie on the DMD. The result is the equivalent of the dual cell in FIG. 3. The light can go from Mirror C to Mirror B and back or from Mirror C to Mirror M and back depending on the state of a given pixel. The DMD decides between the two paths on any particular bounce.

In operation, light comes in from an input source below the unit. Light from the outside source is imaged onto a pixel in the "down" position which acts as a turning mirror. That pixel directs the light to Spherical Mirror 34 which then images it onto a pixel in the "up" position. The pixel then directs the light to Spherical Mirror 35 which images it back to the DMD. The light is now considered to be "in the unit". The choices of tip of the DMD direct the light to the Spherical Mirror 34 and back to Spherical Mirror 35 or to Spherical Mirror 39 and back to Mirror 35. After the last bounce off Spherical Mirror 35, the light goes to Spherical Mirror 39 and to a pixel on the DMD which is in the "up" position and directs the light out of the cell.

In one preferred embodiment of the present invention, a number of input beams are introduced into the device, whose components comprise a spatial light modulator (SLM) and several mirrors. Each beam input into the device bounces back and forth between the SLM and the mirrors, as shown in FIG. 10. Each beam traces a unique path through the device, and each illuminates the SLM in a unique series of focused spots. Each beam is refocused on every pass through

the cell. On any particular pass, the SLM may be addressed at the corresponding pixel such that the selected beam will be switched out of the cell and into another cell or re-imaged onto the output plane. The output plane preferably consists of output ports, or may be any appropriate device such as an SLM or deformable mirror device.

Many beams may be introduced at the input turning mirror, the beams each then progressing through a unique spot pattern. These spot patterns have been discussed previously, so we will not repeat them here. The number of beams that can be circulating through the cell simultaneously is limited only by the number of pixels on the SLM.

A preferred device operates in the following manner. There is an array of N input beams at the input turning mirror. Suppose, to start, that they are arranged in a line of N dots along the input turning mirror, as shown in FIG. 11. The dots all expand to fill Mirror B, and are refocused by that mirror to another line of spots, labeled "1." From there they expand to fill Mirror C, and are re-imaged to the next line of spots on the SLM.

Now suppose the SLM pixel corresponding to spot '4' for a particular beam is addressed. The SLM switches the beam, in this embodiment by changing its polarization. The beam now goes to Mirror E, whose center of curvature is above the beamsplitter. The spot is re-imaged to the row "4" and the column belonging to that particular beam on the output plane.

FIG. 12 shows an example of how 16 input beams are directed to 16 randomly chosen output spots. The bottom is the SLM plane, the top is the output plane. The input beams are along the bottom. The solid spot for each column indicates the addressed pixel. The mapping is indicated in Table 1. Each input beam is mapped to a unique row on the output plane. Note that the output pattern at the top of FIG. 12 is also the pattern of addressed pixels on the SLM.

	*	*	*	*	*	*	*	*	*	*	
	*	*	*	*	*	*	*	*	*	*	
in	1	2	3	4	5	6	7	8	9	10	11
out	10	5	12	2	4	9	16	1	13	15	3
	*	*	*	*	*	*	*	*	*	*	

	*	*	*	
	*	*	*	
12	13	14	15	16
6	8	7	11	14
	*	*	*	

The output plane may be a fiber array or other mechanism for collecting and distributing beams. The array need not be square. Multiple beams may be directed to a single output point if desired. More likely the typical application would be to switch N inputs among N outputs.

To combine all the output spots in row 5, one could use a cylindrical lens. In this embodiment, all spots are focused in the output plane that would land in row "5" to a single output spot "5," as shown in FIG. 13. Alternatively, the beams could be combined using other types of beam combiners such as optical fibers.

The embodiment based on the White cell previously described allows for the interconnection of a large number of optical inputs to a large number of optical outputs. It is also completely reconfigurable and strictly non-blocking. It has, however, the property that the latency and loss that a given input signal experiences depends on the output chosen. For some applications, that can be undesirable.

In another preferred embodiment, the architecture of the interconnection device is modified such that all signals require the same time to propagate through the device, thereby having the same loss.

In the basic interconnection device described previously, there is an input turning mirror that directs an array of beams into a White cell. The White cell consists of a spatial light modulator (SLM) and its lens, and Mirrors B and C. The beams bounce around forming a unique spot pattern on the SLM, but all beams strike the same row on any given bounce number. The beams may be switched out on a particular bounce, and every spot in that row corresponds to a specific output. This much is retained.

In this preferred embodiment, however, once the beam is bounced out of the White cell, it is directed to another spatial light modulator, as shown in FIG. 14. There are two White cells now, each White cell having a spatial light modulator, which could be a DMD as shown in the top of the figure, or a liquid crystal or other polarizing type, as shown in the bottom of the figure. Mirrors B and C and the spatial light modulator labeled "input SLM" constitute the input White cell. Mirror "R" is a relay mirror, which images the first SLM onto a second SLM. The second SLM is also part of an output White cell, consisting of the output SLM and Mirrors E and F.

Considering a particular beam input into the interconnection device, FIG. 15 shows a spot pattern for input "a." On the left is the input SLM (which may be of either type); on the right is the output SLM. Beam "a" follows the bounce pattern dictated by the input White cell, which is determined by the placement of the centers of curvature of Mirrors B and C. If the centers of curvature are placed one above the other as shown in FIG. 15, the input beam under discussion then bounces in the input White cell, forming two columns of spots. On a particular bounce, 4 in this example, the appropriate SLM pixel is switched, sending the beam to Mirror R. The beam then leaves the input cell. (The open circles on the input SLM show where the beam would have struck next if the pixel were not switched.)

The center of curvature of Mirror R is placed between the input and output SLMs. Thus, if input "a" is switched on bounce 4 (input "a" is to be sent to output 4), then the pixel on the input SLM corresponding to column "a" and bounce number 4 (the shaded pixel) is imaged by Mirror R onto the output SLM. The image at the second SLM is then reversed. This is a result of the magnification of - 1 introduced by a single spherical mirror in a 2f-2f imaging configuration.

The second SLM is addressed such that it activates the pixel corresponding to input 'a' and output 4. By "activate" it is meant that that the pixel is switched so that the beam is sent into the output White cell (mirrors E and F). The other pixels may then be set so that the beam continues to bounce in the second White cell.

The second White cell is preferably different from the first, however. The centers of curvature of Mirrors E and F are placed side by side. Thus a given beam, as it propagates in the output cell, forms two rows of spots rather than forming two columns as it did in the input White cell. This means that while the beam continues to propagate through the second White cell, the row (output) information is retained. The large open square indicates the pixel of the last bounce for a given input. In a 9-bounce system that is the 9<th> bounce.

FIG. 16 shows the case for every input switched out of the input cell on bounce 4. This is illustrated for a 9-bounce system. All beams trace out spots in two rows on the output SLM, and they will all end up in the same row again on the 9<th> bounce. (The SLM in this case was made slightly bigger in order to accommodate all spots, as indicated by the dashed lines.) Thus, as in the previous embodiments, a cylindrical (or elliptical) lens may be used to focus all of row 4 onto output 4. In this manner, any beam switched out of the input cell on bounce 4 ends up at output 4.

It will become important later to note that the beam always goes to Mirror E first in the output White cell. The object then is to design the system so that every beam makes a fixed number of bounces, regardless of the specific input and output selected. Then all beams would experience the same latency and the same loss. Thus in a system designed for 9 bounces, a beam destined for output 2 would make 2 bounces in the input cell and finish the rest of its bounces in the output cell. A beam being directed to output 8 would bounce 8 times in the input cell and one time in the output cell.

There is a problem with the arrangement shown in FIG. 16. A conflict can occur, as shown in FIGS. 17 and 18. Here it was intended to direct input "e" to output 4, and input "i" to output 4 as well. Thus on the input SLM, shaded pixels (e,4) and (i,4) are selected. The triangles represent the bounce of beam "e" and the squares represent the bounces of beam "i." The following notation will be used for the bounces in the second White cell. The letter "e" in e<4><6> tells which input beam is being considered. The subscript indicates the desired output (4 in this case) and the superscript tells the bounce number. On output SLM, the spots of beam "e" progress away from the center of the SLM, but at the same time the spots of input "i" are progressing toward the center. It does not matter if bounces from different beams strike the same pixels, as long as the pixels are not ones that need to be activated. In the figure, however, it can be seen that if "e" is to be connected to output 4, then "i" cannot finish its spot pattern. This is because the pixel beam "i" strikes on its 8<th> bounce, which has been already selected to accommodate input "e". Thus input "i" cannot be connected to output 4 at the same time as input "e."

This problem may be gotten around by reversing mirrors E and F. Recall that every beam would visit mirror E first when it entered the output White cell. FIG. 19 illustrates that if the center of curvature of mirror E is placed closer to the center of curvature of Mirror R, the spots on the second White cell will progress away from center rather than toward it. The circles represent the pixels that must be activated to accept a given beam into the output White cell. The square represents the output pixel. Note also that a larger output spatial light modulator is now required.

There is another problem with this scheme, however. We observe that the bounces corresponding to output 4 bounce in two rows, but these are the same rows used by any beams being connected to output 6. The figure shows that to

connect input "a" to output 6, the pixel needed to input the beam into the output White cell is also that which needs to be activated to connect output beam "d" to output 4. That same pixel must simultaneously not be activated to keep the bounces going to direct input "b" to output 4 and input "c" to output 6.

The problem is caused by having the centers of curvature on the horizontal bisector of the output SLM. The solution, then, is to move them below all of the input rows, and extend the size of the output SLM even further. This approach is shown in FIG. 20. Again, the circles represent pixels that may have to be activated in order to connect a particular input to a particular output. The squares may have to be activated to perform a given connection. There is some overlap, the implication of which is that no two inputs may be connected to the same output in this approach.

A preferred embodiment does not actually require two different spatial light modulators. For the arrangement shown in FIG. 20, the output SLM area does not overlap the input area, even if they are on the same plane. Thus a single SLM can be used as shown in FIG. 21. This is not an efficient use of SLM space, however, since much of the area is unused. This can be circumvented by the placement of the mirror centers of curvature as shown in FIG. 22.

The number of pixels needed on the spatial light modulator to interconnect n inputs to m outputs is 4n x m. For example, a small SLM such as is used for television projection might have 480 x 640 pixels, so it could in principle connect 160 inputs to to among 480 outputs. If one desires to have the number of inputs equal the number of outputs, such an SLM could support three separate interconnections, each connecting 160 inputs to 160 outputs.

There is one problem remaining to be solved in this embodiment. When a beam has finished its bounces and is switched out of the output White cell, it will return via Mirror R to the input White cell. This creates a conflict with the bounce patterns in the input cell. One way to circumvent this is to restrict the SLM to a non-polarizing SLM, such as a DMD. Then one can use light of a particular polarization in the input cell. A quarter wave plate may be added in the path to Mirror R as shown in FIG. 23. As the light passes into the second cell, it becomes circularly polarized. It continues its bounce pattern, and when it is switched back out of the output White cell, it passes through the quarter wave plate again at which point it is polarized orthogonal to the input polarization. A polarizing beamsplitter then preferably reflects the output beam out of both cells and into the output optics.

Up to now, dual White cell design has been considered in which spots in one White cell bounce in columns, and in the other cell bounce in rows. This approach has the disadvantage that for a given output connection, the various inputs will all come out at different locations along the output row, requiring a cylindrical lens or the equivalent to combine all the possible output points to one detector or fiber. For example, in FIG. 20, for output number 4, the inputs a-i finish their bounces in a row, but each at a different pixel along that row. It also does not allow multiple inputs to be connected to be the same output.

A more elegant solution, then, is to keep the two White cells but arrange the centers of curvature such that CC(E) is directly above CC(B) and CC(F) is directly above CC(C). In this way when light goes from one White cell to the

other, the bounces remain in the same column but may move up or down between rows. FIG. 24 illustrates this for one input. The solid circles represent the bounces if the beam remains always in the White cell containing Mirrors B and C. The open circles represent the spots for various cases, again using the notation that the subscript indicates the intended destination and the superscript is the bounce number.

Table 2 shows the mirror order used to generate the particular spot pattern in FIG. 24. Actually, there are many possible patterns possible and the mirrors can be visited in different orders than represented in the Table to arrive at the correct output.

One possible set of mirror orders to achieve the spot pattern of FIG. 24:

To send the input to	This pattern of mirrors can be used:
1	BC BC BC BC BC
2	BF EF EF EF EF
3	BC EC BC BC BC
4	BC BF BF EF EF
5	BC BC EC EC BC
6	BC BC BC FB FE
7	BC BC BC EC EC
8	BE CE CE CE FE

Next, multiple inputs may be considered. Where there is a single spot in 24, an array of spots is introduced, represented as a dotted square in FIG. 25. The next move is to move the columns closer together, such as by adjusting the centers of curvature of the mirrors, and move the two triangular regions, indicated with dashed lines, vertically until they meet or overlap. This avoids wasting space on the spatial light modulator.

This approach overcomes the shortcomings of the previously described architecture. Every input spot requires the same number of bounces, regardless of the output selected. Therefore, the latency is the same. The beams all strike the same number of optical elements regardless of the output selected, so the loss is the same. Every input spot in the approach of FIG. 25 strikes a completely unique set of pixels, so now multiple inputs can be connected to the same output. Finally, the need for a cylindrical lens is eliminated. Now any input that is directed to output 8 will appear in the square of spots labeled output 8. This has the advantage in that a common spherical lens may be used to focus all of those spots onto a single detector. This is illustrated in FIG. 26 using a spherical lens array as an example.

The arrangement of FIGS. 24 and 25 both assume that there are four mirrors, B, C, E, and F, and that light can go from B to C, B to F, E to F, or C to E. This flexibility is not necessarily available if the spatial light modulator is a DMD. Considering the simplest example, a two-position DMD device is used as in the configuration of FIG. 27. Here there are three White cell arms that compose two total White cells, one using Mirrors B and C and the other using Mirrors E and C.

In this case, the light can go between Mirrors B and C or between Mirrors E and C. It cannot go directly from E to B, and light must visit Mirror C on every other bounce. The centers of curvature can be arranged as shown in FIG. 28. The center of curvature of Mirror E here is directly above that of Mirror B. A beam bouncing in White cell (BC) will trace out, in general, two rows of spots.

Each time the beam is switched to the other White cell (EC), the next spot will move up one row on the DMD. If there are m bounces, any given input spot can be moved by some number of rows up to m/2. All spots associated with bounce n will still appear in the column associated with bounce n.

FIG. 29 considers one particular input spot and shows how it may be connected to any of 6 outputs. Twelve bounces are required in this case. The gray box also indicates the size of the spot array that may be input without conflict. Any spot in this array can be directed to any of the output squares and thus focused to any output detector. Table 3 shows the order of the mirrors visited by a given beam to achieve the spot pattern shown in FIG. 29. The order may vary. What matters is the number of times the beam goes to Mirror E. Each time the beam goes to mirror E its spot pattern will be shifted by one row.

The mirror pattern used to achieve the spot pattern of FIG. 29.
This is for the 3-arm Dual White cell using a two-position DMD.

Intended output	Order of Mirrors
0	BC BC BC BC BC BC
1	BC BC BC BC BC EC
2	BC BC BC BC EC EC
3	BC BC BC EC EC EC
4	BC BC EC EC EC EC
5	BC EC EC EC EC EC
6	EC EC EC EC EC EC

The arrangement of FIG. 29 can also be implemented with a liquid-crystal-style spatial light modulator and a 4-arm dual White cell. One may superimpose the center of curvature of the fourth mirror (call it F) with the center of curvature of Mirror C.

To summarize this preferred embodiment, an optical interconnection device is implemented using a single spatial light modulator and a few lenses and mirrors. The device is reconfigurable and strictly non-blocking. The preferred versions allow one to independently connect any input to any output (any to any). They also permit the connection of multiple inputs to a single output (many to any). One may connect a single input to multiple outputs (any to many) in the case of a polarization-style SLM by partially changing the polarization on the appropriate bounces such that some of the light energy is switched to the appropriate output. In the case of a DMD-style SLM, such amplitude control could be implemented by dithering the micromirrors. For example, if the beam associated with input "a" is to be sent to two outputs, the micromirrors for the corresponding pixels could be set such that they direct the light to the first output half the time, and the other output the other half of the time. This may require timing things such that the micromirror switching does not interfere with the data, for example making the micromirror switching frequency much faster than the clock rate of the data stream.

It is noted that the optical interconnection device presented here uses a White cell or multiple White cells to generate a spot pattern. The spot pattern is the key to operation of this device, but the spots may be generated by many other optical means, including mirrors, and lenses.

Another photonic device can be made that contains four White cell mirrors, as shown in FIG. 30 for the case where the spatial light modulator is a liquid crystal or other polarizing type. Here there are two White cells, one

consisting of Mirror B, C, and the SLM, and the other consisting of Mirrors E, F, and the SLM. The centers of curvature can be aligned on the face of the SLM. Here, the light beams enter (in an array of spots) on the input turning mirror. From there the beams go to Mirror B and then pass to the SLM. At this point, the beams may each be independently switched. Those that are switched go to Mirror E and have their spot patterns shifted by one row; those that are not switched go to Mirror C and do not have their spots patterns shifted. Returning from either E or C, the light returns to the SLM, from which it may go to F or B. Beams going to F have their spot patterns shifted by one row. Beams going to B do not have their spot patterns shifted.

The connectivity diagram for this cell is shown in FIG. 31. Note that in this case that the light can go directly between Mirrors E and F, which means that the number of row shifts (and thus independent outputs) is now equal to m, the number of bounces, instead of m/2.

A better photonic device may be made by aligning Mirror F such that its center of curvature is displaced from CCB and CCC by amount different than that by which CCE is displaced. Let the number of bounces on the SLM be m.

If a beam is directed to stay in the White cell containing Mirrors B and C for all of its bounces, it traces out a particular spot pattern, forming two rows, and exits at an output corresponding to one of these rows. If the beam is sent once to Mirror E, its spot pattern gets transferred up one row and it will exit at the next output. If the beam goes to Mirror E twice, it will move up two rows, and so forth. The beam may visit Mirror E at most m/2 times, so that in using Mirror E only a beam may be directed to m/2 different to outputs.

If the light is sent to Mirror F, however, the spot pattern may be shifted by a larger amount since F's center of curvature may be displaced by a large amount. It makes sense to choose CCF such that in a single visit to Mirror F the spot pattern is shifted by one more than is possible using Mirror E, or (m/2 + 1) [delta] , where [delta] is the separation between rows of spots.

For example, suppose that m = 20. The beam can visit Mirror E as many as m/2 = 10 times, and thus be transferred to any of 10 different outputs using this mirror alone. If the beam is sent to F one time and E no times, then the pattern is shifted by m/2 + 1 = 11 and the spot exits at the 11<th> output. A visit to E once and F once delivers the beam to output 12. The maximum shift (and thus number of possible outputs) obtainable would be incurred by visiting Mirror F m/2 times to shift a total of (m/2 + 1)m/2 rows and Mirror E m/2 times to shift an addition m/2 rows. The maximum number of outputs, N, then, is <=26> Get Mathematical Equation

We term this a "quadratic cell" because the number of outputs goes as the square of the number of bounces.

A similar device can be implemented using a two-state DMD as shown in FIG. 32. In this figure two axes are established, each containing a White cell. Suppose for example that the DMD had two stable mirror positions, at + 10 [degrees] and - 10 [degrees] . The axes are then chosen such that one lies at + 10 [degrees] and the other lies at - 30 [degrees] with respect to the normal to the DMD plane. On each of the axes is placed two White cell mirrors, one above the plane containing the arms and one below. The White cell whose axis is at 10 [degrees] contains Mirrors A and B. The White cell whose axis is at - 30

[degrees] contains Mirrors E and F. The lenses at the SLM end of the device are not shown. The placements of the centers of curvature, and the connectivity diagram, are also shown it the figure.

If the DMD pixels are all oriented at + 10 [degrees] , then light bounces back and forth between Mirrors A, B, and the DMD. If the pixel corresponding to a particular bounce is switched to - 10 [degrees] then the light is switched to the other White cell. The next pixel is also set to - 10 [degrees] to return the light to the first cell. Light cannot go from Mirror E directly to Mirror F in this configuration. It must first return to the first White cell. Table 4 summarizes the possible transitions.

Possible transitions for the dual White cell.

Micropixel at + 10 [degrees]	Micropixel at - 10 [degrees]
A <= => B	A <= => E
	B <= => F

Tablé 5 shows the direction light will go if incident from various directions with the pixels set in either orientation.

The output angles for rays incident at various angles for the two-position DMD.

Input Angle	Output if pixel at + 10 [degrees]	Output if pixel at - 10 [degrees]
*	*	
10 [degrees]	10 [degrees]	- 30 [degrees]
30 [degrees]	+ 50 [degrees]	+ 10 [degrees]
+ 50 [degrees]	- 30 [degrees]	Don't care
*	*	

Let m be the number of bounces on the DMD. Assume that the light is brought into the cell via an input arm (not shown) that is along an axis at + 50 [degrees] to the normal to the DMD plane. Here, the DMD pixels themselves can be used as input and output turning mirrors. The pixel corresponding to the input spot is set to + 10 [degrees] , and the light will go first from the input arm at + 50 [degrees] into the White cell containing Mirrors E and F. Suppose it is chosen to go to F. On the next bounce, the appropriate pixel is set to - 10 [degrees] , and the beam goes to Mirror B. Now the beam can be directed to go into either cell, and decisions may be made that lead to spot pattern row shifts. Thus, two bounces are required just to input the light into the cell.

Similarly, two bounces may be used for output. Suppose the final path-choice-bounce is on a lower mirror, either B or E. The output arm will necessarily be along the 50 [degrees] axis as well, and to get to this arm the beam must be coming from the EF cell. The light should leave Mirror E, thus headed out upward, so it can be separated from the input beam headed in and upward toward Mirror F. To get to Mirror E in order to be switched out, the light must come from A. Thus two bounces are also required for output.

A total of four bounces are required for input and output if the DMD pixels themselves are used for input and output. This has two disadvantages. One disadvantage is that there will be some energy loss from the extra bounces.

The other disadvantage is that a beam incident on a micromirror at such a large angles as are needed for the input-output arm in this case will have a large footprint on the pixel. An alternative is to use separate input and output turning mirrors. The disadvantage then is the need for more components and the need to align them.

Let us suppose that one chooses to use the pixels as input and output turning mirrors. By the preceding argument, if the total number of time the light bounces on the DMD is m, then the number of times the beam may be switched usefully is four less than that. Let the number of controllable bounces be m' = m - 4.

Let the center of curvature of Mirror E be displaced by one half pixel ([delta]) from the line containing the centers of curvature of Mirrors B and C. Mirror E can only be visited on every other bounce, following a sequence BEBEBEBEBE . . . After any visit to Mirror E, the beam must return to Mirror B according to the connectivity diagram of FIG. 32.

Mirror F may be visited on alternate bounces FCFCFC. It is preferred to displace the center of curvature of Mirror F (CCF) by more than CCE is displaced. This device does not have the same connectivity as the liquid crystal-based cell of FIG. 30, because it is not possible in this case for light to directly from E to F. That is, while a beam can visit Mirror E or Mirror F m'/2 times each, it cannot visit both mirrors E and F that many times. If both mirrors are visited as often as possible, each can be used at most m'/4 times. Thus, the position of the center of Curvature of Mirror F is adjusted to (m'/4 + 1) [delta] away form the line connecting CCB and CCC, and the maximum number of different outputs that a beam can be directed to is ''''' <=27> Get Mathematical Equation

The device is still quadratic but it is quadratic in m/4. This equation predicts that if m = 16, and thus m' = 12, the number of outputs should be 15. It turns out that one may go a little higher. Table 6 shows how to count up to 18 in this case. The input and output bounces are included for completeness. Examining the rows for outputs 16-18 reveals that one may visit Mirror F an extra time, at the expense of a visit to Mirror E. Note that we have chosen the input beam to come in via FC and go out via BE, and that no sequence requires that the beam go directly between E and F. In this example, m'/4 = 3, but Mirror F is visited four times and Mirror E is visited the remaining two times to get to output number 18. Thus the total number of possible different outputs is given by (m'/4 + 1) visits to F (displaced by (m'/4 + 1)), plus (m'/4 - 1) visits to E to with a displacement of 1: '''['']' [''] <=28> Get Mathematical Equation

The mirror progressions for switching a beam to any of 19 different output (including zero) for the cell of FIG. 32. The displacement of the center of curvatures of Mirror E = [DELTA] and F = 4 [DELTA] for m' = 12.

Delay *	Mirror Progression Input	switchable bounces						output
0	FC	BC	BC	BC	BC	BC	BC	BE
1	FC	BC	BC	BC	BC	BC	BE	BE
2	FC	BC	BC	BC	BC	BE	BE	BE
3	FC	BC	BC	BC	BE	BE	BE	BE
4	FC	FC	BC	BC	BC	BC	BC	BE

5	FC FC BC BC BC BC BE BE
6	FC FC BC BC BC BE BE BE
7	FC FC BC BC BE BE BE BE
8	FC FC FC BC BC BC BC BE
9	FC FC FC BC BC BC BE BE
10	FC FC FC BC BC BE BE BE
11	FC FC FC BC BE BE BE BE
12	FC FC FC FC BC BC BC BE
13	FC FC FC FC BC BC BE BE
14	FC FC FC FC BC BE BE BE
15	FC FC FC FC BE BE BE BE
16	FC FC FC FC FC BC BC BE
17	FC FC FC FC FC BC BE BE
18	FC FC FC FC FC BE BE BE
19	No solution

*

Another preferred embodiment utilizes an SLM having more than two states per pixel. Consider a hypothetical DMD whose mirrors can tilt to three different angles, for example + [alpha] , 0, and - [alpha] . A ray incident on such a DMD could be reflected at any of three angles:

[theta] = 2 [alpha] - [phi] (mirror at + [alpha]) or

[theta] = - [phi] (mirror at 0) or

[theta] = - 2 [alpha] - [phi] (mirror at - [alpha])

where [theta] is the angle of reflection with respect to the DMD normal and [phi] is the angle of incidence with respect to the DMD normal. Table 7 shows some possible input angles and the resulting output angles for an arbitrary case in which [alpha] = +/- 10 [degrees] .

Output angles for rays incident at various angles for the three-position DMD.

Input angle	Output if pixel at + 10 [degrees]	Output if pixel at 0 [degrees]	Output if pixel at - 10 [degrees]
5 [degrees]	15 [degrees]	- 5 [degrees]	- 25 [degrees]
10 [degrees]	10 [degrees]	- 10 [degrees]	- 30 [degrees]
15 [degrees]	5 [degrees]	- 15 [degrees]	- 35 [degrees]
20 [degrees]	0 [degrees]	- 20 [degrees]	- 40 [degrees]

Using this DMD device as the common mirror, three White cells may be constructed, labeled I, II, and III, whose axes are at + 2 [alpha] , 0 [degrees] , and - 2 [alpha] to the normal to the DMD plane. For this example, these angles would be 20 [degrees] , - 20 [degrees] , and 0 [degrees] , as shown in FIG. 33. The connectivity is again shown, along with the alignment diagram. Table 8 explains the connectivity diagram. Light from an upper mirror goes to a lower mirror next, and vice versa.

TABL E 8

From	To (pixel + 10 [degrees])	To (pixel 0 [degrees])	To (pixel - 10 [degrees])

*	*	*	
I	II	I	III
II	I	III	(- 40 [degrees])
III	(+ 40 [degrees])	II	I
*	*	*	

There are other possible choices of White cell arm angles, as well, such as + 10 [degrees] , - 10 [degrees] , and - 30 [degrees] . These choices may not be as flexible, as one may not be able to reach as many different arms from a given arm as one can for the choices of 0, +/- 2 [alpha] .

From Table 7 it can be seen that beams may be directed in many directions. Only three are chosen for the next device. In this device, light from Arm I may be directed into either of the other two arms on any bounce. Light from Arm II may go to Arm I or Arm II, but not back into arm II. Similarly, light coming from Arm III may go to II or I, but not back into III. As seen in the connectivity diagram, the mirrors have been arranged differently than they are physically arranged. Physically Mirrors E and H are in different arms, but together with the DMD form a White cell (similarly for G and F).

The mirrors are then preferably aligned as follows. The center of curvature of Mirror E is again one unit displaced from the line containing the centers of curvature of Mirrors B and C. Mirror H is aligned with its center displaced by (m/4 + 1) [DELTA] , where m is the number of bounces on the DMD that are used for switching. Using just these two mirrors, a beam can be shifted by up to [(m/4 + 1)(m/4) + (m/4)] [DELTA] rows. Mirror Mirror G is aligned such that its center is displaced from those of B and C by one more than this, or [] [Delta] [] [Delta] <=29> Get Mathematical Equation

Using, so far, just mirrors E, H, and G, a beam's spot pattern may be shifted over: [[] []] [Delta] [] [Delta] [] [Delta] <=30> Get Mathematical Equation

Finally, the displacement of Mirror F is set such that its center of curvature is displaced by one more: [[] [Delta]] [Delta] [ ] [Delta] [] [Delta] <=31> Get Mathematical Equation

If a given beam is allowed to visit each mirror at most m/4 times, the maximum attainable number of row displacements (outputs) looks like [[] [][]] [Delta] [ ] [Delta] [] [Delta] <=32> Get Mathematical Equation

The number of attainable different outputs is actually one less than this, and Table 9 shows why for a system of m = 8. The input and output bounces have been neglected. From this equation, a maximum row displacement of 80 may be achieved. To arrive at that number, one of mirrors E, F, G, or H would have to be visited on every bounce, but to do that requires going either directly between E and F or directly between G and H, and neither of these transitions is allowed. For every number from 0 to 79 inclusive, however, some order may be found in which to visit the mirrors in order to produce the necessary delay without violating the transition rules.

Thus the actual number of delays attainable is: [] [Delta] <=33> Get Mathematical Equation

This cell is quartic in (m/4).

How to count using the cell of FIG. 33. Take m = 8, E = [DELTA] , H = 3 [DELTA] ,

G = 9 [DELTA] , and F = 27 [DELTA] . The input and output bounces are not shown.

Shift to Output #	Mirror Pattern
*	
0	BC BC BC BC
1	BC BC BC BE
2 (1 + 1)	BC BC BE BE
3	HC BC BC BC
8 (3 + 3 + 1 + 1)	HC HC BE BE
9	BG BC BC BC
12 (9 + 3)	HC BG BC BC
15 (9 + 3 + 3)	HC HC BG BC
18 (9 + 9)	BG BG BC BC
24 (9 + 9 + 3 + 3)	HC HC BG BG
27	FC BC BC BC
30 (27 + 3)	FC HC BC BC
33 (27 + 3 + 3)	FC HC HC BC
36 (27 + 3 + 3 + 3)	FC HC HC HC
39 (27 + 3 + 1 + 3 + 1 + 3 + 1)	FC HE HE HE
40 (27 + 3 + 1 + 9)	FC HE BC BG
42 (27 + 3 + 3 + 9)	FC HC HC BG
43 (27 + 3 + 1 + 3 + 9)	FC HE HC BG
44 (27 + 3 + 1 + 3 + 1 + 9)	FC HE HE BG
45 (27 + 9 + 9)	FC BG BG BC
46 (27 + 9 + 9 + 1)	FC BG BG AE
47 (27 + 9 + 27 + 9 + 1 + 1)	FG FG BE BE
48 (27 + 9 + 9 + 3)	FG BG BC HE
53 (3 + 1 + 3 + 1 + 9 + 27 + 9)	HE HE BG FG
54 (27 + 27)	FC FC BC BC
57 (27 + 27 + 3)	FC FC HC BC
62 (27 + 27 + 3 + 1 + 3 + 1)	FC FC BE HE
63 (27 + 9 + 27)	FG FC BC BC
71 (27 + 9 + 27 + 3 + 1 + 3 + 1)	FG FC HE HE
72 (27 + 9 + 27 + 9)	FC FC BC BC
79 (3 + 1 + 3 + 27 + 9 + 27 + 9)	HE HC FG FG
80 (no solution)	HE HEFG FG
underscored transitions	nor
not allowed	FG FGHE HE
*	

It may be observed that the displacements of the four spot pattern-shifting arms in the quartic cell increase by polynomials in m/4 whose coefficients can be found from the rows of Pascal's Triangle: [] [Delta] [] [Delta] [] [Delta] <=34> Get Mathematical Equation [] [Delta] <=35> Get Mathematical Equation

These ideas may be extended to optical interconnection devices based on digital micromirror devices that have more than three stable micromirror positions.

Another optical element that may be used in an optical interconnection system of the present invention is a roof prism. Light incident normally on the diagonal face of a roof prism will be totally internally reflected from the two roof surfaces. It is a well-known property of the roof prism that the light beam exiting the roof will be parallel to the input beam. Thus, a ray leaving the

spot on the right in the figure will arrive at a new spot on the left. A roof prism may also comprise two discrete mirrors, oriented with some angle between them. The angle need not necessarily be 90 [degrees] .

To generate a proper spot pattern using the roof prism, various things may be done. First, the hypotenuse face of the roof prism may be angled slightly with respect to the spatial light modulator, such that as a beam bounces back and forth between the two sides of the roof prism, it also progresses forward or backward along the direction of the prism ridge. Multiple beams may be introduced, which would each strike a unique set of spots on the spatial light modulator.

Alternatively, one could rotate the roof prism about the ridge such that the hypotenuse face of the roof prism is tilted slightly with respect to the spatial light modulator. In this case the beams progress outward on the SLM. Multiple input beams may again be used.

Positions of successive spots may be found in the following manner. Consider a 90 [degrees] roof prism whose base has a half-width of W and that has a height of W. The y-axis is then placed along the base and the z-axis through the apex as shown in FIG. 34. Next, consider a ray inside the prism travelling at an angle [alpha] with respect to the z-axis. Since Ray 1 has a slope of [alpha] , the equation for Ray 1 may be written as:

y = [alpha] z + y<n>

where y<n> is the y-intercept of the ray, the point at which it intersects the base of the prism. Next, the equation for Side 1 of the prism may be written, Side 1 having a slope of 1 and a y-intercept of - W.

y = x - W.

Solving for the intersection obtains the point A = (z<A>,y<A>) where [alpha] [alpha] [alpha] <=36> Get Mathematical Equation

in which we must find the y-intercept b. We have a known point on this line, Point (A) given by the equation for z<A> above, so substituting that point in obtains: [alpha] [alpha] [alpha] [alpha] [alpha] [alpha] [alpha] [alpha] [alpha] [alpha] [alpha] <=37> Get Mathematical Equation

The equation for Ray 2 is thus [alpha] [alpha] [alpha] [alpha] <=38> Get Mathematical Equation

Ray 2 also intersects the upper side of the roof prism, the equation for which is

y = - z + W.

The intersection of above equations for Ray 2 is point B. Solving for the coordinates finds: [alpha] [alpha] [alpha] [alpha] [alpha] [alpha] [alpha] [alpha] <=39> Get Mathematical Equation

Point B also lies on Ray 3, the equation for which is

y = [alpha] z + b = [alpha] z + y<n + 1>

where it has been noted that the y-intercept of Ray 3 is the position y<n + 1>, to be found. Plugging in coordinates (z<B>, y<B>) results in [[alpha] [alpha] [[alpha] [alpha] [alpha]]] <=40> Get Mathematical Equation

To find the positions at which these rays intersect the flat mirror, Rays 1 and 3 have only been extended to the SLM plane. If that plane is a distance L away from the apex of the roof prism, and the roof prism has a height of h = W, then at the SLM plane the coordinates are

y<n>' = y<n> - [alpha] (L - W)

y<n + 1>' = y<n + 1> - [alpha] (L - W).

These equations only apply when the input ray (Ray 1) strikes the lower half of the roof prism. If it strikes the upper half first, the above procedure is followed in reverse, intersecting Ray 1 with the upper mirror first. The result is: [[alpha] [alpha] [[alpha] [alpha] [alpha]]] <=41> Get Mathematical Equation

Deciding which equation to use may be done in the following way. If the ray is allowed to continue to the plane z = L, and it crosses that plane above the y-axis, then it will strike the upper side of the roof prism first, as shown in FIG. 35. Thus if y(z = L) > 0, the first equation for y<n + 1> should be used; if y(z = L) < 0, the second equation for y<n + 1> should be used. The spots may progress inward or outward, or first inward and then outward. The last case is the most useful because the beams may be introduced into the cell at the outside edge of the flat mirror, bound inward, then outward, and be extracted at the opposite, or same, outside edge.

FIG. 36 shows the spots that would result if an input spot were introduced at the position x = 201, whose ray has a slope of - 0.1, and was directed at a prism whose apex was 100 units from the input plane. Note that these spots would actually land in a line of constant y; the plot shown in FIG. 36 stretches them out to show the order of progression. The spots in this case progress inward and then outward. The spacing between successive spots is constant.

In a situation in which the SLM is not parallel to the hypotenuse face of the roof prism, another progression of spots is generated. In this case, however, the image plane (the SLM) is not perpendicular to the optical axis, and spots will tend to be magnified or demagnified going from one side of the SLM to the other. If the SLM is tilted around the x-axis, the spots will grow or shrink as they progress away from center. If the flat mirror is tilted in the y-z plane, then each beam will have two spot sizes as it progresses down the mirror, one on the - x side and the other on the + x side.

The point is made again that any of these spot patterns may be generated with combinations of mirrors and lenses. A roof prism is shown only because it is expected to have less energy loss. Each pixel of the SLM or DMD is assumed to have the ability to tilt out of the plane of the DMD in one or more directions. For example, FIG. 37 shows the case for a DMD in which all pixels are turned to the same orientation. The DMD mirror plane is tipped with respect to the roof prism hypotenuse face, but each of the individual pixels is parallel to that face.

The entity in FIG. 37 will be referred to as a Prism cell. The prism cell can be configured in many different ways. Next, the mirrors are allowed to switch between two stable orientations, for example +/- [theta] . Then, a beam bouncing around in one cell can be switched out on any particular bounce. A second-cell can then be added, as shown in FIG. 38.

The preferred embodiments herein disclosed are not intended to be exhaustive or to unnecessarily limit the scope of the invention. The preferred embodiments were chosen and described in order to explain the principles of the present invention so that others skilled in the art may practice the invention. Having shown and described preferred embodiments of the present invention, it will be within the ability of one of ordinary skill in the art to make alterations or modifications to the present invention, such as through the substitution of equivalent materials or structural arrangements, or through the use of equivalent process steps, so as to be able to practice the present invention without departing from its spirit as reflected in the appended claims, the text and teaching of which are hereby incorporated by reference herein. It is the intention, therefore, to limit the invention only as indicated by the scope of the claims and equivalents thereof.

CLAIMS:
What is claimed is:

[*1] 1. A free-space optical interconnection device comprising:(a) at least one input light source, said at least one input light source adapted to generate an array of light beams; (b) a plurality of optical elements configured so as to define a plurality of possible light paths for each said light beam in said array; (c) a spatial light modulator adapted to select a path from among said light paths for each pass of a said light beam through said optical elements and reflect the light beam to said selected path, each said light beam making multiple passes through said optical elements; and (d) an output plane adapted to receive each said light beam emerging from said optical elements, said output plane having at least two dimensions, the resultant position of each said light beam on the output plane determined in one said dimension by the position of said light beam in one dimensional input array and in the other said dimension by said light paths traveled by said light beam through said optical elements.

[*2] 2. An optical interconnection device according to claim 1 additionally comprising an input mirror adapted to reflect said one dimensional array of light beams into said plurality of optical elements.

[*3] 3. An optical interconnection device according to claim 2 wherein said input mirror is adjustable.

[*4] 4. An optical interconnection device according to claim 1 additionally comprising at least one receiving device adapted to receive a said light beam emerging from said optical elements.

[*5] 5. An optical interconnection device according to claim 1 wherein said output plane is selected from the group consisting of spatial light modulators, fiber arrays, and beam collecting devices.

[*6] 6. An optical interconnection device according to claim 1 wherein said plurality of optical elements is selected from the group consisting of mirrors, lenses, gratings, and prisms.

[*7] 7. An optical interconnection device according to claim 1 additionally comprising an output mirror adapted to direct a said light beam emerging from said optical elements to said output plane.

[*8] 8. An optical interconnection device according to claim 1 additionally comprising at least one refocusing optical element adapted to restrict the divergence of a light is beam diverted by said optical elements through at least one of said light paths.

[*9] 9. An optical interconnection device according to claim 1 wherein said spatial light modulator consists of a polarizing spatial light modulator adapted to change the polarization of a said light beam directed to said spatial light modulator.

[*10] 10. An optical interconnection device according to claim 9 additionally comprising a beam splitting device adapted to direct a said light beam along a said light path depending on the polarization of the light beam.

[*11] 11. An optical interconnection device according to claim 1 wherein said spatial light modulator consists of a deformable mirror device spatial light modulator.

[*12] 12. An optical interconnection device according to claim 1 additionally comprising an optical receiving device for each possible position of an output beam on said output plane.

[*13] 13. An optical interconnection device according to claim 12 wherein said optical receiving device comprises an optical fiber.

[*14] 14. An optical interconnection device according to claim 1 additionally comprising a number of optical receiving devices equal to the number of possible light beams in said input array.

[*15] 15. An optical interconnection device according to claim 14 wherein each optical receiving device comprises an optical fiber.

[*16] 16. An optical interconnection device comprising:(a) an input light source, said input light source adapted to generate at least one individual light beam from at least one direction; (b) a first optical configuration, said first optical configuration comprising: (i) a first plurality of optical elements configured so as to define a plurality of possible light paths for each said light beam; and (ii) a first spatial light modulator adapted to select a path from among said light paths for each pass of a said light beam through said first plurality of optical elements; (c) a second optical configuration, said second optical configuration adapted to receive as input said light beams emerging from said first optical configuration, said second optical configuration comprising: (i) a second plurality of optical elements configured so as to define a plurality of possible light paths for each said light beam emerging from said first optical configuration; and (ii) a second spatial light modulator adapted to select a path from among said light paths for each pass of a said light beam through said second plurality of optical elements; and (d) at least one receiving device adapted to receive a said light beam exiting said second optical configuration, said optical configurations adapted so that a similar period of time is needed for each said light beam to pass from said input light source through said optical configurations to said receiving

device.

[*17] 17. An optical interconnection device according to claim 16 additionally comprising an input mirror adapted to reflect said at least one individual light beam to said first optical configuration.

[*18] 18. An optical interconnection device according to claim 17 wherein said input mirror is adjustable.

[*19] 19. An optical interconnection device according to claim 16 additionally comprising an output mirror adapted to reflect each said light beam emerging from said second optical configuration.

[*20] 20. An optical interconnection device according to claim 19 wherein said output mirror is adjustable.

[*21] 21. An optical interconnection device according to claim 16 wherein said first optical configuration additionally comprises at least one first refocusing optical element adapted to restrict the divergence of a light beam diverted by said first plurality of optical elements through at least one of said light paths.

[*22] 22. An optical interconnection device according to claim 16 wherein said second optical configuration additionally comprises at least one second refocusing optical element adapted to restrict the divergence of a light beam diverted by said second plurality of optical elements through at least one of said light paths.

[*23] 23. An optical interconnection device according to claim 16 wherein said input light source is adapted to generate an array of light beams.

[*24] 24. An optical interconnection device according to claim 16 wherein said first and second pluralities of optical elements are selected from the group consisting of mirrors, lenses, gratings, quarter wave plates, and prisms.

[*25] 25. An optical interconnection device according to claim 16 wherein a said spatial light modulator consists of a polarizing spatial light modulator adapted to change the polarization of a said light beam directed to said spatial light modulator.

[*26] 26. An optical interconnection device according to claim 25 additionally comprising a beam splitting device adapted to direct a said light beam along a said light path depending on the polarization of the light beam.

[*27] 27. An optical interconnection device according to claim 16 wherein a said spatial light modulator consists of a deformable mirror device spatial light modulator adapted to reflect a said light beam to at least one of said plurality of light paths.

[*28] 28. An optical interconnection device comprising:(a) an input light source, said input light source adapted to generate at least one individual light beam from at least one direction; (b) a first optical configuration, said first optical configuration comprising: (i) a first plurality of optical elements configured so as to define a plurality of possible light paths for each said light beam; and (ii) a spatial light modulator adapted to select a path

from among said light paths for each pass of a said light beam through said first plurality of optical elements, said first optical configuration adapted to use a first portion of said spatial light modulator; (c) a second optical configuration, said second optical configuration adapted to receive as input said light beams emerging from said first optical configuration, said second optical configuration comprising: (i) a second plurality of optical elements configured so as to define a plurality of possible light paths for each said light beam emerging from said first optical configuration; and (ii) a second portion of said spatial light modulator adapted to select a path from among said light paths for each pass of a said light beam through said second plurality of optical elements, said second portion of said spatial light modulator having no reflective elements in common with said first portion; and (d) at least one receiving device adapted to receive a said light beam exiting said second optical configuration, said first and second optical configurations adapted so that a similar period of time is needed for each said light beam to pass from said input light source through said configurations to said receiving device.

[*29] 29. An optical interconnection device according to claim 28 additionally comprising an input mirror adapted to reflect said at least one individual light beam from said input light source to said first optical configuration.

[*30] 30. An optical interconnection device according to claim 29 wherein said input mirror is adjustable.

[*31] 31. An optical interconnection device according to claim 28 additionally comprising an output mirror adapted to reflect each said light beam emerging from said second optical configuration to said at least one receiving device.

[*32] 32. An optical interconnection device according to claim 31 wherein said output mirror is adjustable.

[*33] 33. An optical interconnection device according to claim 28 wherein said first optical configuration additionally comprises at least one first refocusing optical element adapted to restrict the divergence of a light beam diverted by said first plurality of optical elements through at least one of said light paths.

[*34] 34. An optical interconnection device according to claim 28 wherein said second optical configuration additionally comprises at least one second refocusing optical element adapted to restrict the divergence of a light beam diverted by said second plurality of optical elements through at least one of said light paths.

[*35] 35. An optical interconnection device according to claim 28 wherein said input light source is adapted to generate an array of light beams.

[*36] 36. An optical interconnection device according to claim 28 wherein said first and fail second pluralities of optical elements are selected from the group consisting of mirrors, lenses, gratings, quarter wave plates, and prisms.

[*37] 37. An optical interconnection device according to claim 28 wherein a said spatial light modulator consists of a polarizing spatial light modulator adapted to change the polarization of a said light beam directed to said

spatial light modulator.

[*38] 38. An optical interconnection device according to claim 37 additionally comprising a beam splitting device adapted to direct a said light beam along a said light path depending on the polarization of the light beam.

[*39] 39. An optical interconnection device according to claim 28 wherein a said spatial light modulator consists of a deformable mirror device spatial light modulator adapted to reflect a said light beam to at least one of said plurality of light paths.

[*40] 40. An optical switching apparatus comprising:(a) at least one input optical fiber, each said input optical fiber adapted to carry an optical signal; (b) a first optical configuration, said first optical configuration comprising: (i) a first plurality of optical elements configured so as to define a plurality of possible light paths for each said optical signal; and (ii) a first spatial light modulator adapted to select a path from among said light paths for each pass of a said optical signal through said first plurality of optical elements; (c) a second optical configuration, said second optical configuration adapted to receive as input a said optical signal emerging from said first optical configuration, said second optical configuration comprising: (i) a second plurality of optical elements configured so as to define a plurality of possible light paths for each said optical signal emerging from said first optical configuration; and (ii) a second spatial light modulator adapted to select a path from among said light paths for each pass of a said optical signal through said second plurality of optical elements; and (d) a plurality of output optical fibers, each said output optical fiber adapted to carry a said optical signal exiting said second optical configuration, said first and second optical configurations adapted such that a similar period of time is needed for each said optical signal to pass from a said input optical fiber to a said output optical fiber.

[*41] 41. An optical switching apparatus according to claim 40 additionally comprising an input mirror adapted to reflect said optical signal from said optical fiber to said first optical configuration.

[*42] 42. An optical switching apparatus according to claim 41 wherein said input mirror is adjustable.

[*43] 43. An optical switching apparatus according to claim 40 additionally comprising an output mirror adapted to reflect each said optical signal emerging from said second optical configuration to a said output optical fiber.

[*44] 44. An optical switching apparatus according to claim 43 wherein said output mirror is adjustable.

[*45] 45. An optical switching apparatus according to claim 40 wherein said first optical configuration additionally comprises at least one refocusing optical element adapted to restrict the divergence of a said optical signal diverted by said first plurality of optical elements through at least one of said light paths.

[*46] 46. An optical switching apparatus according to claim 40 wherein said second optical configuration additionally comprises at least one refocusing optical element adapted to restrict the divergence of a said optical signal

diverted by said second plurality of optical elements through at least one of said light paths.

[*47] 47. An optical switching apparatus according to claim 40 wherein said first and second pluralities of optical elements are selected from the group consisting of mirrors, lenses, gratings, quarter wave plates, and prisms.

[*48] 48. An optical switching apparatus according to claim 40 wherein a said spatial light modulator consists of a polarizing spatial light modulator adapted to change the polarization of a said optical signal directed to said spatial light modulator.

[*49] 49. An optical switching apparatus according to claim 48 additionally comprising a beam splitting device adapted to direct a said optical signal along a said light path depending on the polarization of the light beam.

[*50] 50. An optical switching apparatus according to claim 40 wherein a said spatial light modulator consists of a deformable mirror device spatial light modulator.

[*51] 51. An optical switching apparatus according to claim 40 wherein said first and second spatial light modulators comprise separate regions of a single spatial light modulator.